

Roadway Delineation Practices Handbook

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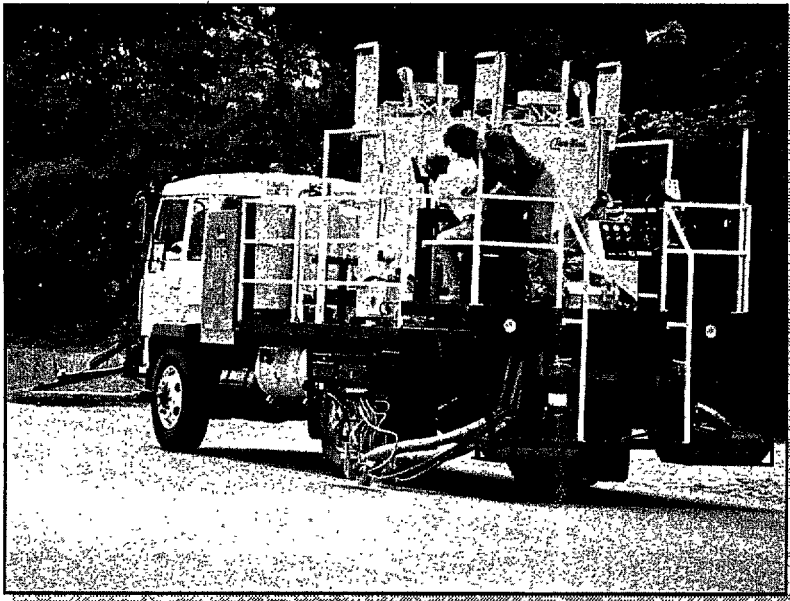
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ROADWAY DELINEATION PRACTICES HANDBOOK

August 1994



Innovation Through Partnerships



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16. Abstract <p><i>The Roadway Delineation Practices Handbook</i> was developed to assist design, traffic, and maintenance engineering personnel in making determinations about roadway delineation systems, including the appropriate system for a given situation, when a system has reached the end of its useful life, and how to maintain a quality delineation system. It may also be valuable to consulting engineers, educators, and students.</p> <p>A companion videotape, <i>Testing and Field Inspection of Roadway Delineation</i>, was produced to assist engineers with field inspection of the quality of delineation projects. This videotape is available separately as publication number FHWA-SA-93-002.</p> <p>This Handbook supplements the policies and standards provided in the <i>Manual on Uniform Traffic Control Devices</i> by offering implementation guidelines for the standards. The contents cover current and newly developed devices, materials, and installation equipment, presenting each item's expected performance based on actual experience or field and laboratory tests. The Handbook draws on the experiences of Federal, State, county, and city agencies and summarizes future directions and developments as reported in recent research and by industry's technical representatives. Individual chapters cover the characteristics of retroreflection and quality assurance, driver visibility needs, traffic paints, preformed tapes, raised pavement markers and other marking materials, post-mounted delineators and other delineation devices, and administrative and management issues and practices. The appendices provide detailed technical information, including cost analysis techniques; sources of materials and equipment; and a list of standards, specifications, and test methods related to delineation.</p>					
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yards	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.765	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: Volumes greater than 1000 l shall be shown in m ³ .				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.71	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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ABBREVIATIONS

AASHTO:	American Association of State Highway and Transportation Officials
AC:	Asphaltic Concrete
ADT:	Average Daily Traffic
ASTM:	American Society for Testing and Materials
ATSSA:	American Traffic Safety Services Association
BTU:	British thermal unit
DOT:	Department of Transportation
E:	Rate of superelevation
EPA:	Environmental Protection Agency
ETP:	Epoxy Thermoplastic Paint
F:	Coefficient of friction
FHWA:	Federal Highway Administration
id:	Inner Diameter
L:	Length
mil:	One-thousandth of an inch
MUTCD:	Manual on Uniform Traffic Control Devices for Streets and Highways
NASHTO:	Northeastern Association of State Highway and Transportation Officials
NCHRP:	National Cooperative Highway Research Program
NCSHS:	National Conference on Street and Highway Safety
od:	Outer diameter
PCC:	Portland Cement Concrete
PIEV	Perception, Identification, Emotion, and Volition Time
r,R:	Radius
RI:	Refractive Index
R_A :	Specific intensity per unit area
R_L :	Coefficient of Retroreflected Luminance
RPM:	Raised Pavement Marker
s:	Spacing of delineators on curves
SASHTO:	Southeastern Association of State Highway and Transportation Officials
SRTF:	Southeastern Regional Test Facility
V:	Velocity
v o c :	Volatile Organic Compound

CHAPTER 1. INTRODUCTION

BACKGROUND

Motor vehicle ownership and use continue to rise in all sectors of the nation. The corresponding increase in accidents, delays, and inconvenience has posed a critical challenge to highway and traffic operations and safety engineers. In seeking solutions, the emphasis has shifted from new road construction to improvement of existing roadways.

Roadway delineation techniques have generally kept pace with the development of the national highway and street systems. Delineation has long been considered essential for effective guidance of the driver. This guidance enhances traffic flow, driving comfort, and traffic safety. Shrinking highway budgets, however, make it important to use new and improved economical delineation methods. A thorough knowledge of the technology and prudent application of cost-effective techniques are needed.

Definition of Delineation

Delineation refers to any method of defining the roadway operating area for the driver. In this Handbook, delineation is defined as one, or a combination of devices (excluding guide signs), that regulate, warn, or provide tracking information and guidance to the driver. These devices include the following delineation materials: painted markings, thermoplastic and other durable markings, raised pavement markers, and post-mounted delineators. Warning signs are also considered part of the delineation system. They are used to complement standard delineation in special areas, such as at horizontal curves.

The function of roadway markings, as stated in the *Manual on Uniform Traffic Control Devices (MUTCD)*, part 3, is to “supplement the regulations and warnings of other devices such as traffic signs or signals. In other instances, they are used alone and produce results that cannot be obtained by the use of any other device... [by] conveying certain regulations and warnings that could not otherwise be made clearly under-standable.”

The *MUTCD* presents standard ways of conveying information to the driver (design, color, pattern, and width). For example, yellow lines separate traffic flowing in opposing directions, whereas white lines denote traffic flowing in the same direction. Broken lines are permissive in character; solid lines are restrictive. Width of the line indicates its emphasis. Detailed standards related to color, pattern, and width are presented in *MUTCD* sections 3A-2 through 3A-6, where it is stressed that “each standard marking shall be used only to convey the meaning prescribed for it in this Manual [*MUTCD*] .” In this Handbook, it is assumed that personnel who design roadway delineation will be familiar with the *MUTCD* or its State-mandated equivalent.

In a properly designed traffic control system, markings have specific functions. Pavement markings guide the movement of traffic and promote safety on the highway. In some cases, they are used to supplement the messages of other traffic control devices. In other cases, markings are the only way to convey a message without distracting the driver. In addition, a highway’s capacity increases from orderly traffic flow. Pavement markings encourage this kind of capacity increase.

Markings must be readily understood, and this can be achieved only by a uniform system of markings. A motorist should see the same type of markings in different localities and these markings should impart the same message wherever they are encountered.

Initiatives to Improve Highway Safety

Because highway agencies are beginning to concentrate on increasing capacity for existing roadways, safety has become more important than ever.

While the 1990 rate of 2.1 traffic fatalities per 100 million vehicle miles traveled is the lowest in United States history, much work remains.⁽²⁾ There were almost 6.5 million police-reported traffic accidents resulting in more than 44,000 fatalities in 1990.⁽³⁾

One of the primary goals of engineers is the application of new technology to old problems. Engineers attempt to make life easier and safer for the public. The use of innovative delineation techniques and treatments can have safety benefits for drivers in ways that may not be realized with any other method.

On October 3, 1983, the Secretary of Transportation announced a series of new initiatives directed toward improving highway safety. The Secretary's initiatives included several items directed specifically toward actions in the Federal Highway Administration's (FHWA's) area of program responsibilities. The FHWA's memo, dated October 25, 1983, set forth objectives and methods for implementing the initiative on highway safety delineation and markings.⁽⁴⁾ One hundred percent Federal funding was made available for implementing the delineation initiative.

Cost-Effective Markings

The best known way to improve capacity and safety on highways is to provide cost-effective delineation. This means applying markings that provide the longest service life per unit cost, provided performance is equal.

Benefit-Cost Ratio

Markings should be evaluated by the use of the benefit-cost ratio. First, all options must provide nearly equal visibility for their effective service lives. This is of paramount importance. If this criterion is not adhered to, the most cost-effective option will seem to be a low-cost, low-performance system that may eventually create a hazard because of its rapid failure or degraded visibility early in its lifetime.

Appendix A (Cost Analysis Techniques) gives a quantitative definition of how the benefit-cost ratio may be used to evaluate marking alternatives.

Conditions for Cost-Effective Systems

Cost-effectiveness will be obtained by considering all variables and by thinking of delineation as a system that consists of the pavement material, the marking material, and the retroreflective material. It is vital that the delineation variables for each application (discussed in chapter 2) are treated with an appropriate marking system.

In addition, there are a multitude of other variables that enter the equation. The length of time the markings will be needed, local availability of materials and equipment, and the marking agency's policies and liabilities are just a few. The highway engineer must realize that trade-offs must often be made among a multitude of divergent and often conflicting concerns. This is the only way that the optimum cost-effective delineation system can be attained.

SCOPE OF THE RESEARCH

The FHWA, National Cooperative Highway Research Program (NCHRP), and other agencies have sponsored research to improve roadway delineation. In addition, many States and some large cities have conducted laboratory and field tests of new delineation techniques. Many of these small agencies, however, do not have the resources to investigate the devices, materials, or equipment that are a part of an effective roadway delineation system. These agencies need guidance that is more objective than the persuasiveness of the local vendor.

Recognizing this need, the FHWA initiated a project to develop a Handbook on roadway delineation systems. This Handbook would be intended to assist the practicing engineer in determining the appropriate system for a particular situation.

This Handbook does not establish FHWA policies or standards. Rather, it is meant to supplement the *Manual on Uniform Traffic Control Devices*, offering guidelines for implementing the standards presented in the *MUTCD*. This Handbook is not intended to be a technical report on research into the latest delineation technologies. However, major research findings used to develop guidelines are clearly referenced. Those interested in the details of a particular research project should seek them independently.

This Handbook is intended primarily for use by design, traffic, and maintenance engineering personnel. It may also prove valuable to consulting engineers, educators, and students. The contents cover current and newly developed devices, materials, and installation equipment, presenting each item's expected performance based on actual experience or field and laboratory tests.

While this Handbook is not meant to reflect the state of the art in delineation

technology, it does provide fundamental concepts. The materials used to develop the Handbook reflect the experience of Federal, State, county, and city agencies. It also summarizes future directions and developments as reported in recent research and by industry's technical representatives.

HANDBOOK ORGANIZATION

The *Roadway Delineation Practices Handbook* provides the practicing engineer with a guide for selecting the best delineation technique for a given set of circumstances. The subject matter falls into six parts:

- Introduction and background (chapter 1).
- Delineation visibility factors (chapters 2 and 3).
- Technical description of current delineation practices (chapters 4 through 10).
- Summary of administrative and management issues and practices (chapters 11 and 12).
- Technical supplement (appendices).

When possible, the chapters with technical descriptions of delineation techniques have been written in a common format. To avoid redundancy, material that is similar for many techniques is detailed in chapter 4 and referenced in subsequent chapters.

The appendices provide detailed technical information to supplement the basic practices described in the text. Of particular interest to the practicing traffic or maintenance engineer will be the appendix A, which explains the cost analysis technique for evaluating pavement markings. Appendix B gives the names and addresses of agencies that sell delineation-related products. Finally, appendix C gives information about delineation specifications.

CHAPTER 2. CHARACTERISTICS OF RETROREFLECTION AND QUALITY ASSURANCE

INTRODUCTION

Today, delineation is an established component of the highway system. The question is no longer one of whether delineation is effective, but rather one of how to provide the best system of delineation for the least cost.

Retroreflectivity is vital for a delineation system to be effective at night. Delineation is intended for visual guidance of the driver; nighttime visibility is almost directly proportional to retroreflectivity. This chapter, therefore, covers the most important aspect of roadway delineation: achieving durable retroreflective markings to ensure long-life visibility. Also discussed are quality assurance through material testing and the programs sponsored by the Federal Highway Administration (FHWA) to encourage testing.

RETROREFLECTION

Highway agencies' recognition of the importance of retroreflection have made its use nearly universal. According to the *Manual on Uniform Traffic Control Devices (MUTCD)*, markings that must be visible at night should be retroreflective unless ambient illumination assures adequate visibility.⁽¹⁾ Because the percentage of well-illuminated roadways is so small, the trend among highway agencies is to make all pavement markings retroreflective. The common exceptions are painted curbs and parking lines.

General Principles

A 1987 FHWA report by McGee and Mace defines *retroreflection* as the phenomenon of light rays striking a surface and being redirected directly back to the source of light.⁽⁵⁾ (See figure 1.)

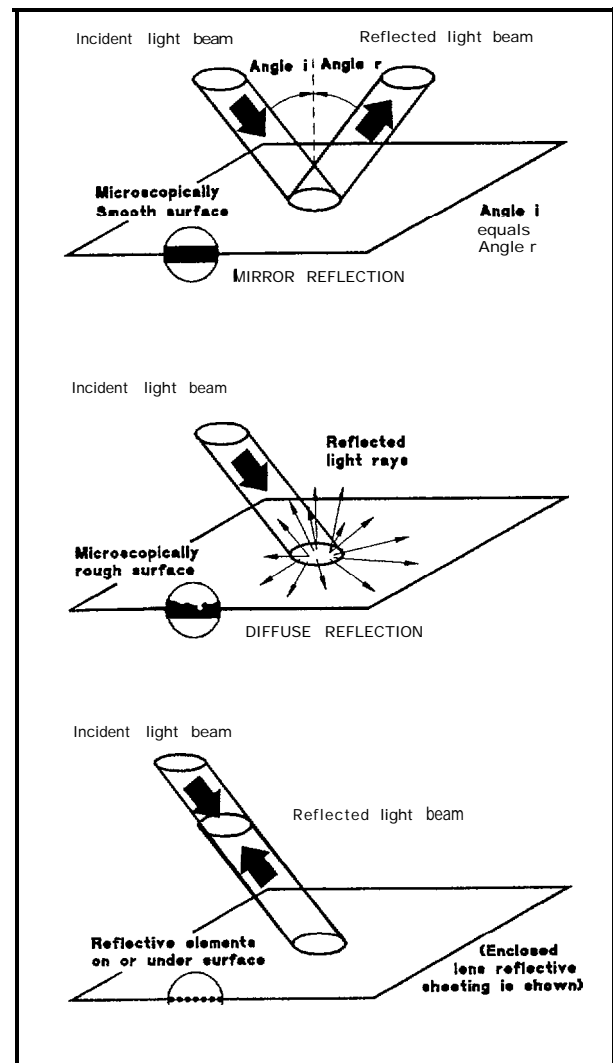


Figure 1. Types of reflection

To understand this phenomenon, a discussion of optical characteristics is necessary. Light sources emit some amount of energy in the form of visible light. An ideal point light source directs its light equally in all directions (figure 2a). If a perfect point light source were enclosed in a perfect sphere, every point on the sphere would be illuminated by an equal amount of brightness, or intensity.

A directed light source, such as a flashlight, will direct its light in a cone around the direction that it is pointed, as seen in figure 2b. If the flashlight puts out an amount of light energy equal to the point

flow rate of light energy. Light flux can be compared to the flow rate of water; it describes how much light is flowing per unit of time.

Using the same analogy, intensity is like the velocity of water flow. If there are two pipes that discharge equal amounts of water every second, and one pipe's cross-sectional area is half that of the other pipe, it is clear that the velocity of water in the smaller pipe must be twice that of the water flowing from the larger pipe.

The same is true for light. If there are two directed light sources that release the

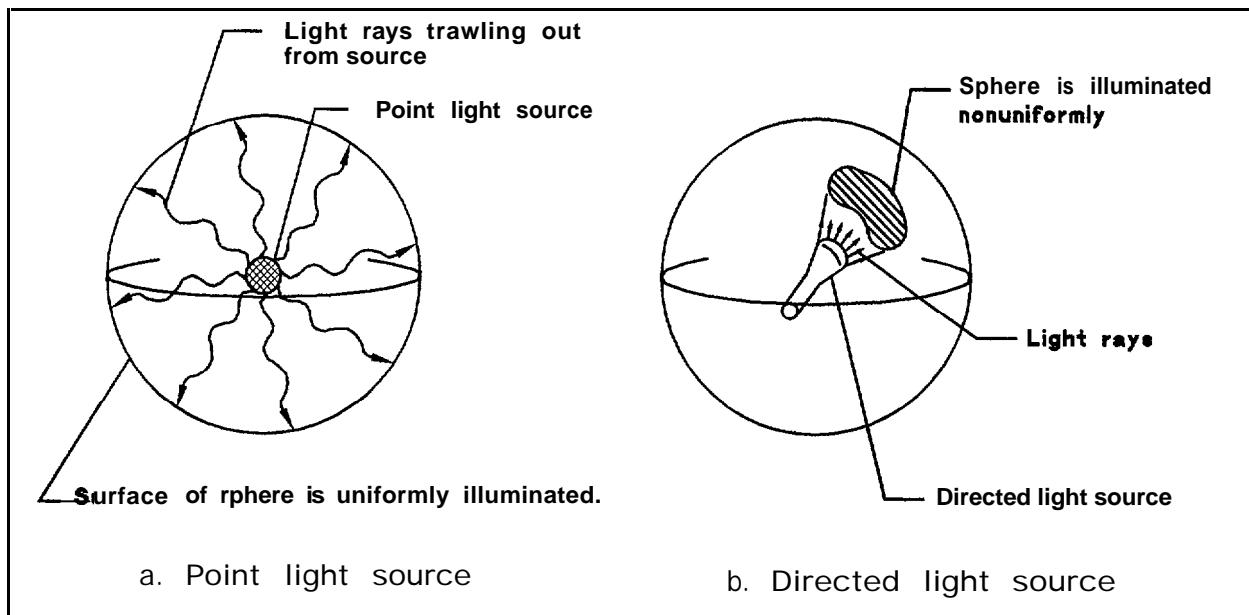


Figure 2. Comparison of point and directed light sources

source, and is enclosed in an identical perfect sphere, the intensity of light from the flashlight falling on each point will be greater than that of each identical point on the sphere with the point source. Simply put, the points on which the flashlight shines will be brighter than each point illuminated by the point source.

For the sake of complete accuracy, *light flux* and how it relates to energy are described, since these two concepts are not strictly identical. Rather, light flux is a

same total light flux, but the first source illuminates twice the area of the second, the intensity of the second source will be twice that of the first. This may be visualized as "squeezing" the light rays together to get the same amount of light onto a smaller area. As a result, the area illuminated by the second source will appear brighter, just as the water in the smaller pipe will travel faster and flow with more water per unit of area.

These concepts can aid in an understanding of the phenomenon of retroreflectivity. A point light source, like the one described above, has a uniform distribution of light flux in all directions around it, as shown in figure 2a. A perfect retroreflector would simply reverse the direction of the light incident upon it. In all directions except that of the source, the intensity of light emitted from the reflector is zero.

A perfect retroreflector would not be useful for roadway delineation, since all reflected light would be returned directly to the auto headlights. (See figure 3a.)

Fortunately, retroreflectors are not perfect. Some light is absorbed by the reflector. More importantly, there is a scattering of light intensity in directions around that of the source, as in figure 3b. It is this imperfectly retroreflected light that returns to the driver's eyes and allows retroreflection to be useful for pavement markings.

Measuring Retroreflection

Hoffman and Firth suggest an ideal way to measure the retroreflective properties of a device.⁽⁶⁾ It seems intuitively correct to measure retroreflection as a ratio of the intensity of light returned in the direction of the driver to the intensity of the source. This would give a scale for retroreflection that consisted of a dimensionless number between 0 and 1.

Unfortunately, there are pragmatic problems with this approach and there must therefore be a system of units to define light flux, intensity, and other optical quantities. The following sections show how these units have been used to establish standard test methods for measuring retroreflection.

Units of Measure

Metric Units

To aid this discussion of units, the concept of a *solid angle* will be defined. A solid angle is a measure of how large an

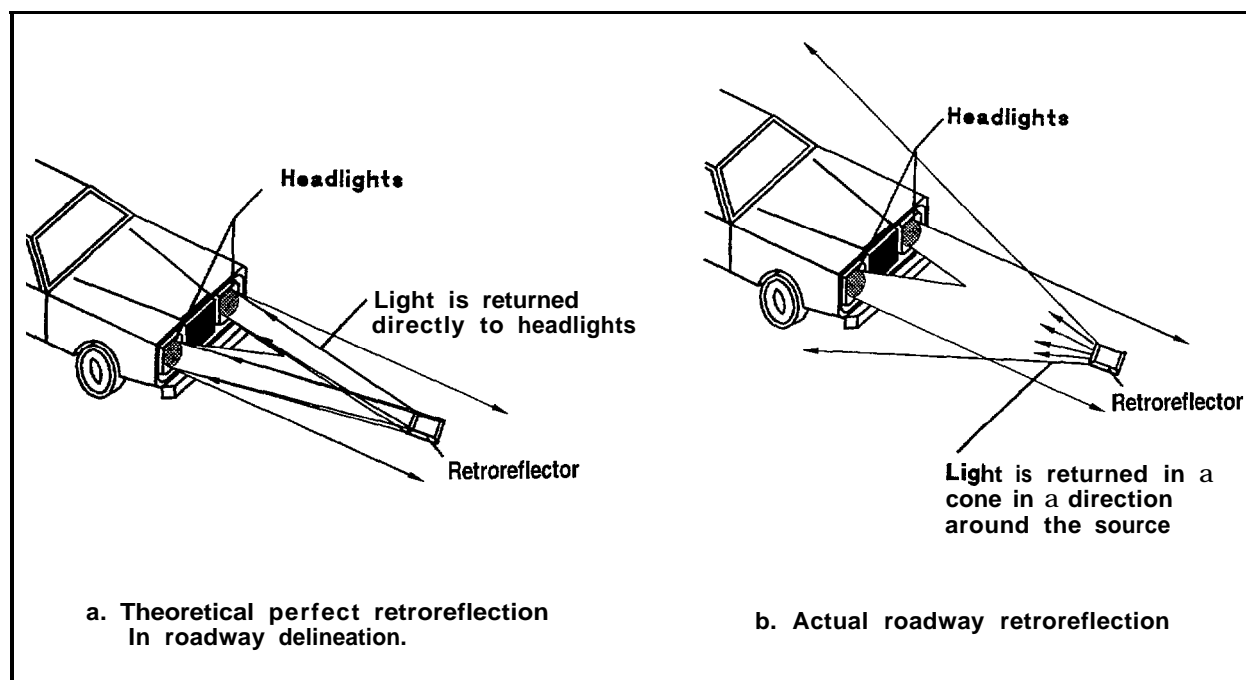


Figure 3. Comparison of theoretical and actual retroreflection

object “looks” from a certain vantage point. The solid angle subtended by an object (or arbitrary area) is a function of the object’s area projection in the direction of the vantage point and its distance from the vantage point.

Solid angles are measured in units called steradians (s). Steradians are defined so that there are a total of 4π steradians in a complete sphere around a source. This is analogous to the two-dimensional case where 2π radians equals a complete circular angle around a point.

In figure 4, the solid angle subtended by Area ABCD is equal to the area of ABCD, divided by the total area of the concentric sphere, times the total number of steradians in the sphere.

$$= \frac{1\text{m}^2}{4\pi(1\text{m})^2} \times 4\pi \text{ (s)} = 1 \text{ steradian}$$

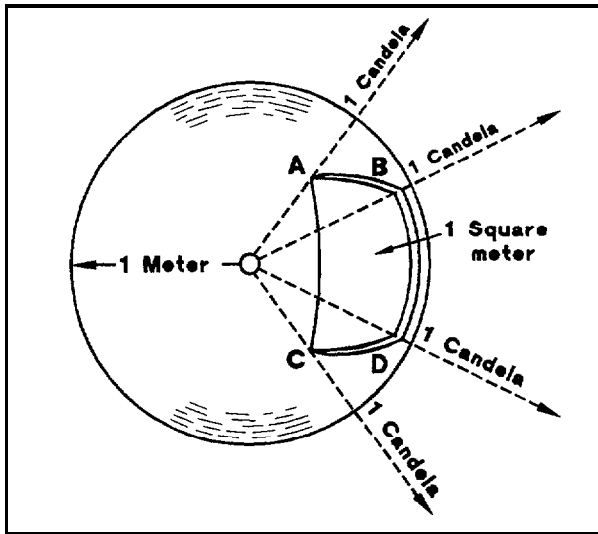


Figure 4. Intensity of a light source

Having defined the solid angle, the definition of optical quantities can be presented. The basic optical quantity is the *candela*. It is a measure of luminous intensity. The concept of intensity was discussed in the previous section. The official definition adopted in 1979 by the General Conference on Weights and Measures is: “The candela is the luminous

intensity in a given direction of a source emitting a monochromatic radiation of frequency 540×10^{12} Hertz, the radiant intensity of which in that direction is $1/683$ watts per steradian.” This definition, while not helpful for an intuitive grasp of the nature of luminous intensity, does provide a physical means to establish optical units.

With this definition to establish the candela as the basic optical unit, a unit of flux can be defined. As described earlier, *flux* is a measure of total light energy emitted per unit of time. The unit of flux is called the *lumen*. One lumen is defined as that amount of light energy flowing through a solid angle of one steradian from a source having a luminous intensity of 1 candela.

Illuminance is defined as the luminous flux per unit area. It is measured in units of *lux*, or lumens per square meter. In other words, if a uniform light flux of 1 lumen is falling on an area of 1 square meter, then the illuminance at any point on the surface is 1 lux. (See figure 4.) The illuminance on area ABCD is 1 lux (1 lumen per square meter).

In figure 4, the area ABCD is 1 square meter. Its solid angle with respect to the point source at the center of the sphere is 1 steradian. If the point source is uniform with an intensity of 1 candela, then the flux falling on area ABCD is 1 lumen. The illuminance at any point on area ABCD is 1 lumen per square meter or 1 lux. The sphere has a total area of $4\pi r^2$ or 12.57 square meters. A flux of 1 lumen falls on each square meter, so the total power output of the source is 12.57 lumens.⁽⁶⁾

Figure 5 illustrates the difference between *intensity* and *illuminance*. Suppose the lines passing through A,B,C, and D in figure 4 are extended until they subtend an area of 4 square meters. A sphere with a radius equal to their distances from the source will have a radius of 2 meters.

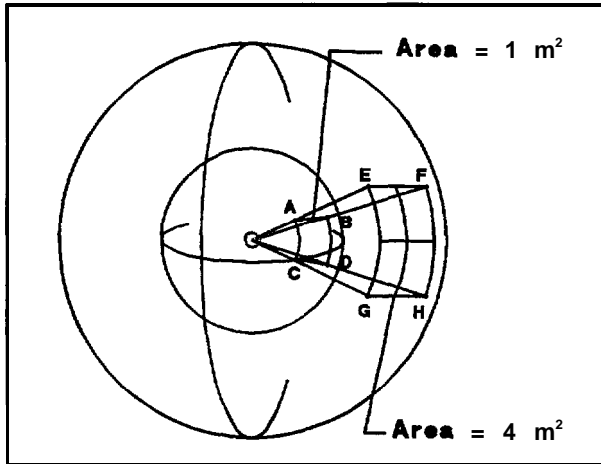


Figure 5. Distribution of light through space

The solid angle subtended by EFGH will be equal to that of ABCD:

$$\text{solid angle} = \frac{4\text{m}^2}{4\pi(2\text{m}^2)} \times 4\pi \text{ (s)} = 1 \text{ (s)}$$

And, since the source's intensity equals 1 candela, or 1 lumen per steradian, there is still a total flux of 1 lumen on Area EFGH. However, the illuminance at any point on EFGH is now:

$$= \frac{1 \text{ lumen}}{4 \text{ m}^2} = 0.25 \text{ lumen/m}^2 = 0.25 \text{ lux.}$$

Obviously, the illuminance on a surface decreases with the square of the distance from the source.

In simpler terms, intensity measures the brightness of a source, and illuminance measures the brightness of light on a surface that is illuminated. These are not the same because the light that a source puts out is spread out over a larger region as it radiates through space. These statements are generalizations for a spatially uniform point source. They do not apply to a directed source, because the light is not spread out over so large a region of space, but they do serve to help illustrate a concept.

English Units

English units are similar to Metric units. Candelas and lumens are identical in the English system. Illuminance, however, is measured with units of lumens per square foot rather than per square meter. One lumen per square foot is a footcandle and one footcandle equals 10.76 lux (lumens per square meter).

Coefficient of Retroreflected Luminance-Markings

The most commonly used measure of retroreflectivity for markings is *coefficient of retroreflected luminance*, R_L . It is defined by the American Society for Testing and Materials (ASTM) to be the ratio of the luminance, L , of a surface to the normal illuminance, E_L , on the surface. Luminance is defined as the luminous flux of a light ray on a surface per unit of projected area of that surface, per unit of solid angle.⁽⁷⁾ One of the main problems with measuring retroreflection in the past has been that standards like these were written with laboratory testing procedures in mind. These standards do not translate well into test methods that work in the field, however.

In the field, this definition of R_L would translate to measuring the luminance of the marking to the normal illuminance of the incident light on the marking. In this context, the luminance would be the luminous flux of a light ray from the marking to the driver, per unit of projected area of the marking in the direction of the driver, per unit of solid angle. Additionally, since luminous intensity is just luminous flux per unit solid angle, the luminance is simply the luminous intensity of the light returned by the marking per unit area. The normal illuminance, E_L , is the illuminance of the headlights on the marking, measured on a plane perpendicular to the direction of the headlight beams.

Figure 6 helps visualize these quantities. If the car shown is frozen at a specific instant of time, then the observation and illumination angles are fixed. The headlights direct light of a specific intensity along the illumination axis. Since the quantities defined in the standards are directional, a single point must be identified on the marking where R_L will be examined. This point will be point B in figure 6. Having established this, a precise definition of the illumination axis is possible, directed along line AB in figure 6.

By the time the light reaches point B, it has been “spread out” through space and will have a certain illuminance associated with it. A plane is placed at point B with an area of 1 square meter, and a normal vector in the same direction as line AB. The value of illuminance at B will equal the amount of light that would fall on this plane if it were all illuminated by the same intensity of light as that directed at point B.

The light will be reflected back in a cone shape around the direction of the source. It will have a certain intensity in the observation direction, along line BC.

At this point, the standards are no longer helpful. Using the two values just mentioned, a value for coefficient of luminous intensity can be calculated. To calculate luminance and derive a value for

R_L , the luminous intensity per unit area must be found. The problem is in selection of the appropriate area to divide by. Up to this point, all the quantities have been directional, dealing with infinitesimal areas. If a very small area is chosen, the illuminance will be uniform, but how large should the area chosen be, and at what angle? If a larger area is chosen, illuminance will not be uniform and the flux must be integrated over the area and then divided by the total area. If a unit area is chosen, then its inclusion does not affect the value of the coefficient at all. If the entire area illuminated by the headlights is used, there is again the problem of nonuniform illuminance, since some areas illuminated are much farther from the headlights than other areas.

What really happens is decided by the manufacturer of the retroreflection-measuring instrument. The illuminance on some arbitrary area is measured and this is used as the sample area. The problem of non-uniform illuminance is not so important because the scale of the instrument is usually much smaller than that of automobile headlights, and the instruments therefore shine light on a small area.

Such decisions result in coefficients of retroreflection that differ from one instrument to another, depending on each instrument's sample area and method of

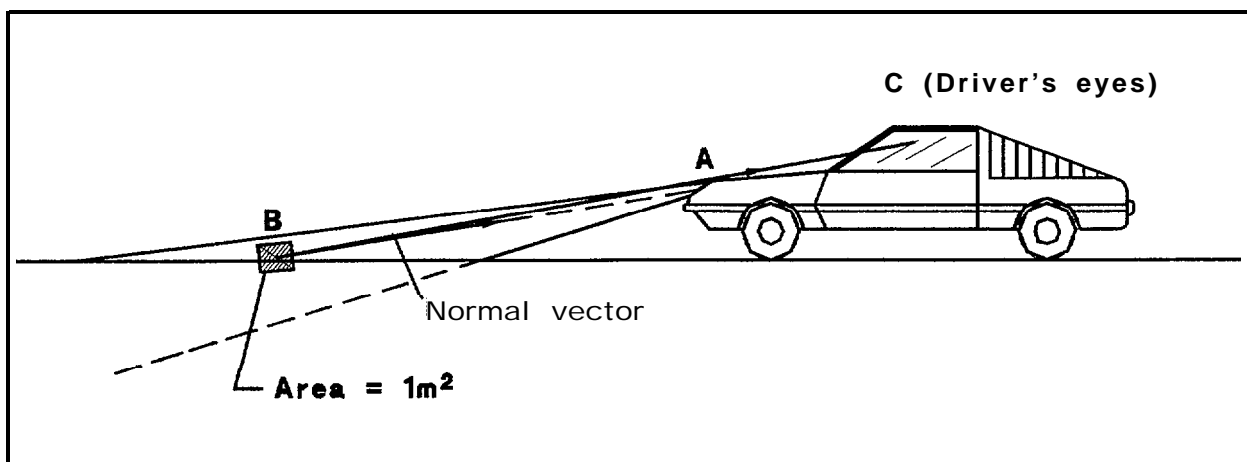


Figure 6. Physical quantities related to roadway retroreflection measurement

measuring intensity and illuminance. Care must be taken to prevent use of these values interchangeably for different instruments.

Each instrument can usually be relied upon to be consistent with itself. The method used by each should be constant, and will result in units of candelas per lux per square meter. The unit of 1 candela per lux per square meter, however, is too large to be practical. The unit used in actual practice is millicandelas per lux per square meter, which is equal to one-one thousandth of the basic unit.

As was originally mentioned, much of this problem arises from the attempt to apply laboratory test methods to field testing. The lack of flexibility in the standards, and incompleteness of terms and methods defined by the standards result in makeshift, inconsistent retroreflection-measuring instruments. At the time of publication of this Handbook, no official ASTM standard exists for a field test method for measuring retroreflection, but plans are reportedly being made to develop one.

Coefficient of Retroreflection-Signs

Coefficient of retroreflection (R_A) is the standard used for signs and is described by *ASTM Standard E808-91*.⁽⁸⁾ It is defined as the coefficient of luminous intensity, R , of a plane retroreflecting surface to its area, expressed in metric units of candelas per lux per square meter. The coefficient of luminous intensity is defined as the luminous intensity, I , of the retroreflector in the direction of observation to the illuminance at the retroreflector on a plane perpendicular to the direction of the incident light. After all of the units and other considerations are taken into account, R_A is conceptually identical to coefficient of retroreflected luminance, but is simpler to implement for signs. Also, the English units of candelas per footcandle per square foot are often used for R_A , and it is also

often referred to as specific intensity per unit area (SIA).

R_A is still a ratio of returned intensity to incident illuminance divided by the area of the retroreflector. Signs make the measurement of these quantities simpler, however, because they have a fixed area. The measuring geometry is arranged so that the plane of the sign is perpendicular to the incident illumination; the illuminance is uniform across the face of the sign. This makes measurement much simpler and more accurate.

Glass Beads

Definition

Glass beads are small glass spheres used in highway signs and pavement markings to provide the necessary retroreflectivity. The beads are applied to pavement markings in one of three ways. They can be dropped on, they can be premixed in marking materials before application, or a portion can be dropped onto premixed materials.

The most commonly used technique is spraying (under pressure) or dropping (by gravity) a quantity of beads onto the wet material. The bead nozzle is located immediately behind the paint nozzle or extrusion shoe so that the beads are sprayed or dropped almost simultaneously with the paint application. For beads to retroreflect light, two bead properties are necessary: transparency and roundness. Beads made of glass have both of these properties. Early experiments in the use of crushed glass and aluminum or brass beads proved these materials to be unacceptable because they failed to meet these criteria.

The need for transparency and roundness can be explained by examining the path of light as it enters a bead embedded in a painted marking. First, the glass bead must be transparent so that light can pass into the sphere. As the light ray

enters the bead, it is bent (refracted) downward by the rounded surface of the bead to a point below where the bead is embedded in the paint. Light striking the back of the paint-coated bead surface is reflected back toward the path of entry (figure 7). If the paint were not present, the light would continue through the bead and bounce in many directions. Characteristics, typical uses, and major factors influencing the application of glass beads are discussed in the following sections.

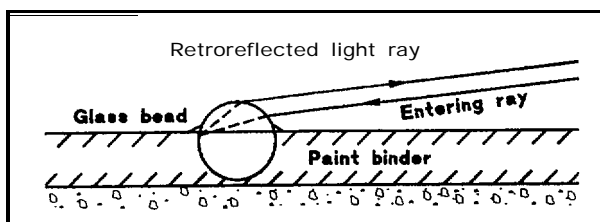


Figure 7. Glass bead retroreflection

Physical Description

The light that glass beads retroreflect is a function of three variables: index of refraction; bead shape, size, and surface characteristics; and the number of beads present and exposed to light rays.

The *refractive index* (RI) is a function of the chemical makeup of the beads. The higher the RI, the more light is retroreflected. Beads used in traffic paint commonly have an RI of 1.50. There are some 1.65 RI beads used with thermoplastic; 1.90 RI beads are often used in retroreflective airport markings.

The chemical composition of glass beads differs for each refractive index. The 1.50 RI bead is a hard soda lime glass made from crushed scrap windowpane glass, called cullet. Both 1.65 and 1.90 RI beads are manufactured from raw materials.

Despite the increased brightness gained with the higher refractive index, most State and local highway agencies use 1.50 RI beads. Because these beads are made from cullet, a recycled product, they are less

expensive than those manufactured from raw materials. They are more stable chemically and require fewer pounds per gallon of marking material because they are less dense than higher RI beads. Also, the higher index beads are more brittle and therefore need to be replaced more often. Some highway agencies use a mixture of 1.50 and 1.65 RI beads on roadways, and a few supplement the 1.50 RI beads with 1.90 RI beads.

Glass beads range in size from 60 micrometers (0.0024 inches) to 850 micrometers (0.034 inches). Bead size usually is expressed in terms of U.S. sieve number, or the size of the mesh screen that a bead will pass through. For example, a U.S. Sieve Number 20 will permit beads with a diameter of 840 micrometers (0.033 inches) or less to pass through the mesh; a number 200 mesh will allow only those beads of 74 micrometers (0.0029 inches) or less to pass.

A typical application of drop-on beads will use from 20 to 100 mesh. The specified gradation, or percentage of weight for each size bead, is a subject of some debate. It is usually a local policy decision based on several factors. First, the realities of marking application and the uncertainties of weather and material control must be considered when selecting bead gradations. Second, the drying time of the marking material affects settlement of the beads into the binder. Obtaining equal embedment in a quick-drying material requires smaller beads. Third, service life of the material and number of beads applied affect bead gradation. A durable thermoplastic material application with 10 pounds per gallon of premix and drop-on beads requires a wide range of bead gradation. Conversely, a painted marking with an expected service life fewer than four months and an application rate of 4 pounds per gallon of beads has a narrower range of sizes. Finally, beads that are too small (80 to 100 mesh) are very light and may be blown away. Also, very large beads may be lost

early because they are poorly anchored. New binder materials alleviate this problem.

Retroreflective Properties

Each glass sphere works like a light-focusing lens. Each has a definite focal point outside the back of the bead. The closer the focal point is to the back surface of the sphere, the brighter the light return. For example, as shown in figure 8, the 1.50 RI bead has a focal point further behind the back of the bead than does the 1.65 RI bead. With the 1.90 RI bead, the focal point is very close to the bead's back surface. Consequently, a marking with 1.90 RI beads will be brighter than one using 1.65 or 1.50 RI beads.

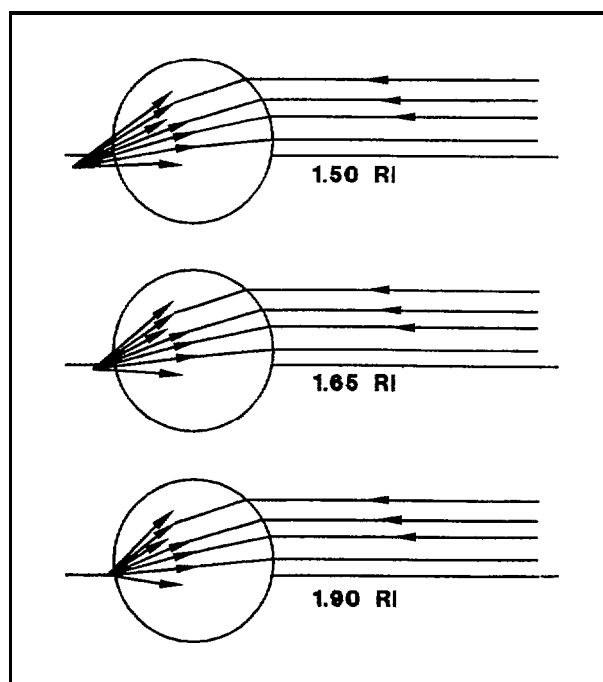


Figure 8. Effect of refractive index on glass bead retroreflection

Since the light is actually focused outside the back of the sphere, the light that is incident on the back of the bead is in the shape of a semicircular bright "spot." (See figure 9.)

This light passes through to the paint binder, where it is scattered. This makes

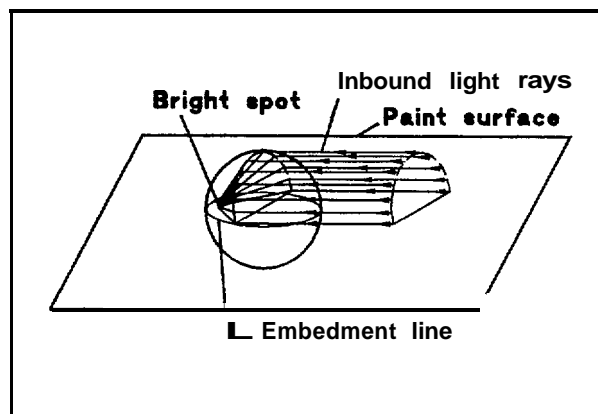


Figure 9. Focusing effect of glass beads

the binder act as another light source, located on the side of the bead opposite the driver. Good retroreflection, therefore, is dependent not only on the quality and quantity of beads, but also on the quality and quantity of high index pigment in the pavement marking's binder.

The light that is retroreflected forms a cone directed toward the driver, after it is focused by the glass bead. As a direct result of the glass bead's optical characteristics, the bright spot on the back of the glass bead turns out to be about 60 percent of the diameter's distance from the top.⁽⁹⁾ Accordingly, the bead's retroreflectivity should rise sharply at about 60 percent embedment, as the bright spot must strike the binder and undergo diffuse reflection for the bead's proper functioning. Also, retroreflectivity would be expected to fall off gradually as embedment increases and the proportion of the reflected cone that is returned toward the driver decreases. This is in fact what occurs for a single bead. (See figure 10.)

For a marking on the road with many beads, other factors (such as meniscus formation of paint on the bead, and collected light being passed on to beads farther away from the driver) change the optimum value. For a pavement marking, the actual value for optimum performance is between 55 and 60 percent embedment.⁽⁹⁾

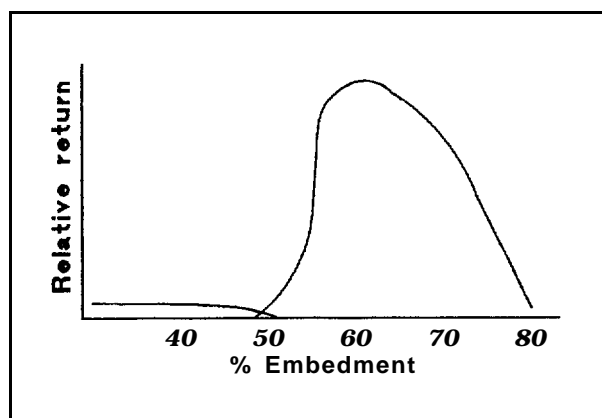


Figure 10. Optimum glass bead embedment

Bead Size

Until recently, the use of very large glass beads to increase retroreflectivity of pavement markings has been limited. The materials experienced a significant loss in retroreflectivity over time due to increased wearing away of the large glass beads.

In recent study, Kalchbrenner investigated the feasibility of using these very large glass beads in a pavement marking system implementing improved synthetic binders and resin materials, especially thermoplastic, polyester, and epoxy markings.⁽⁹⁾ He found that large beads (40 mesh or greater) enhance a marking's retroreflectivity. When used with an appropriate binder system, they can be quite durable as well. Figure 11 shows large versus standard bead performance as measured with a MiroLux retroreflectometer.

Large glass beads are especially effective when roads are wet. Figure 12 shows how a water film (thickness equal to 10 percent of the bead's diameter) influences the lens effect of a glass bead. The top figure shows the same bead in dry conditions. Calculations show that a bead having a diameter two or three times larger will make the effect of the same thickness of film negligible, as this thickness will be very small compared to the large bead's diameter.⁽¹⁰⁾

Large glass beads can have a beneficial effect under certain conditions. Once again, it is stressed that delineation systems must consider all the important variables when selecting bead gradations.

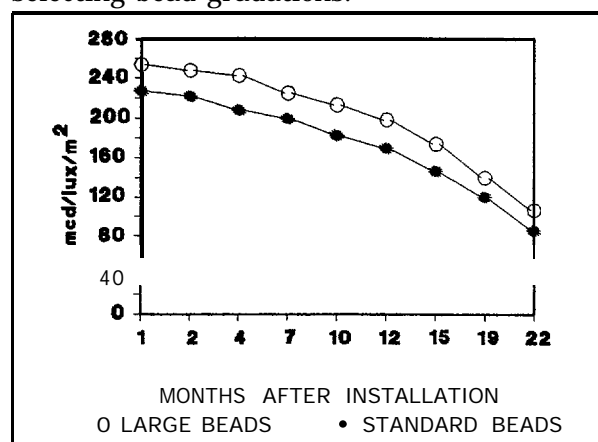


Figure 11. Large vs. standard bead performance in epoxy pavement markings

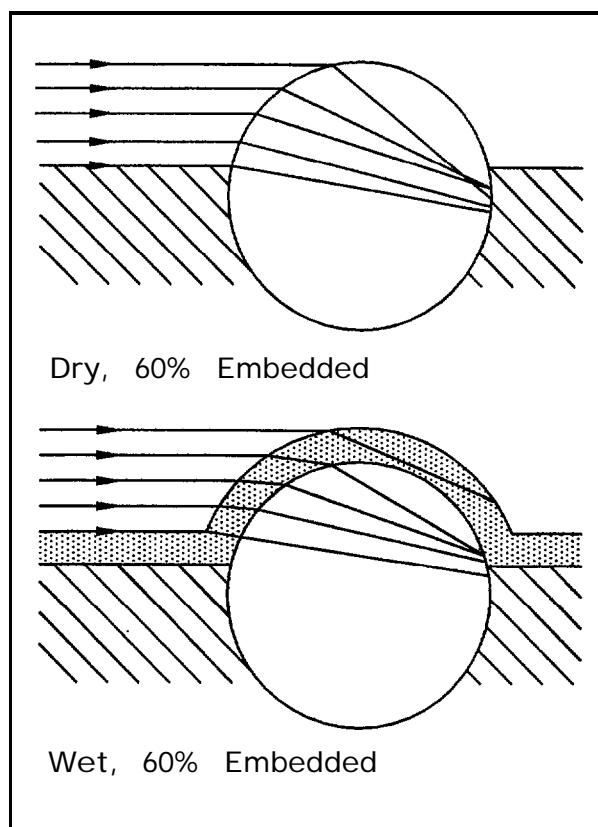


Figure 12. Water films' effect on retroreflection

In an effort to provide for all-weather pavement markings, the FHWA has

developed three new gradations of large glass beads, as alternative beads, for use in water base paint, epoxy, polyester, and thermoplastic marking materials. These gradations, which range from sieve size No. 8 to No. 25, are shown in table 1. Application rates of the larger size beads in the above materials are shown in FHWA's FP-92.⁽¹¹⁾ Field tests show use of the larger beads provides good visibility of markings at night in the rain.

Premixed Paint

To obtain greater durability and better distribution of beads, fine gradation beads (60 to 200 mesh) can be added to the paint formulation to produce a "retroreflective paint." The initial retroreflectivity of premixed paint is poor since very few beads are exposed. As the marking is subjected to traffic, the thin coating covering the beads is worn away. The retroreflectivity improves markedly and is retained for a significantly longer period of time. Initial retroreflectivity can be achieved by dropping

coarse gradation beads on the premixed paint.

During the 1960s and early 1970s, about 20 percent of the State highway agencies used premixed paint supplemented by drop-on beads. Although the durability and brightness of the markings was judged superior, a number of problems were reported. The settlement of beads in the paint during storage was an acute problem at first, but was solved in part by using smaller beads and a suitable suspension agent in the paint formulation. Drum rolling equipment and stirring **devices** were also developed to alleviate the problem.

A number of premix users reported excessive wear of paint spray nozzles. Paint crews generally exhibit little enthusiasm for this technique as they perceive it to be "more trouble than it's worth." As a result, only a few major premix users remain despite the technique's superior performance.

Table 1. Gradations for FHWA Type 3, Type 4, and Type 5 large glass beads.

Sieve Size	Percent by Weight Passing Designated Sieve (ASTM D 1214)		
	Grading Designations		
	Type 3	Type 4	Type 5
No. 8 (2.36 mm)			100
No. 10 (2.0 mm)		100	95 - 100
No. 12 (1.7 mm)	100	95 - 100	80 - 95
No. 14 (1.4 mm)	95 - 100	80 - 95	10 - 40
No. 16 (1.18 mm)	80 - 95	10 - 40	0 - 5
No. 18 (1.0 mm)	10 - 40	0 - 5	0 - 2
No. 20 (850 um)	0 - 5	0 - 2	
No. 25 (710 um)	0 - 2		

Flotation Beads

To improve the performance of conventional glass beads, manufacturers have developed a *flotation bead*. Flotation beads are standard glass beads treated with a special chemical substance that causes all of them, large and small, to float in wet paint rather than sink completely into the paint film (figure 13). Because all the beads are thereby exposed, a brighter marking is theoretically attained.

The two major advantages associated with flotation beads involve application and performance. Flotation beads provide a more consistent level of brightness. All beads float so that half of the bead is exposed regardless of variations in paint film thickness. With standard beads, a heavy application of paint will submerge a large portion of beads, thereby reducing initial brightness.

Flotation beads are more expensive than standard beads by several cents per pound, which could be significant to highway agencies purchasing millions of pounds of beads annually. This additional cost can be partially recovered, however, because fewer pounds of the smaller beads are required to provide the same level of retroreflectivity. For example, 4 pounds (1.8 kilograms) of the smaller beads produce more reflective bodies than 6 pounds (2.7 kilograms) of the mixed gradation.

Knowing this, a highway agency can specify a lower number of pounds of beads per gallon of marking material, with an increased percentage by weight of smaller beads. This will effectively increase, or at least keep constant, the total number of retroreflective bodies in the marking. This technique would be ineffective with a standard-beaded marking because many of the smaller bodies would sink below 50 percent of their diameter, and therefore become nonretroreflective, especially in thicker marking materials.

A problem with flotation beads arises under certain conditions. In areas where roads are often wet and the markings are covered by a water film, flotation beaded markings might experience decreased retroreflectivity. If the percentage by weight of smaller beads is increased, wet retroreflectivity will be reduced due to the effect of the water films discussed in the previous sections.

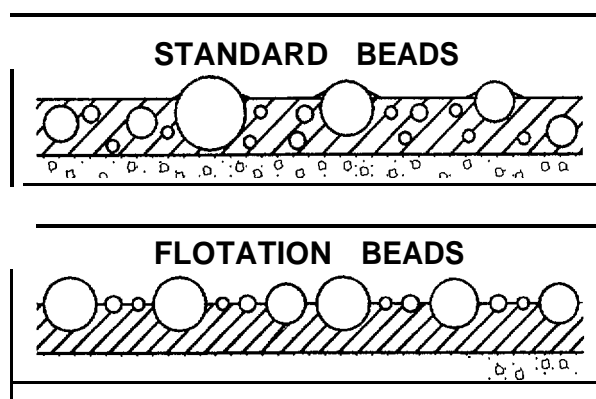


Figure 13. Flotation beads

Also, flotation beads are of limited use in systems requiring the application of beads by pressure spray. For example, in systems using hot-applied, fast-drying paints, the paint skims over so rapidly that the beads are applied only partly into the paint spray under pressure. Some of the beads are therefore covered by the paint and will not float.

Because no flotation beads are sunk under the surface of the marking, a flotation beaded marking is often not as durable as a standard beaded marking. As the paint film wears, the larger beads will be lost quickly because they are not embedded as deeply as they might be in a standard beaded or premixed marking. There are no beads under the surface to become exposed as the paint wears. As a result, flotation beads normally are used as a means to increase initial retroreflectivity when a long service life is not as important.

Common Problems

In areas of high humidity, drop-on glass beads tend to absorb moisture and lose their free-flowing property. Moisture absorption is due to the bead's large ratio of surface area to volume. The beads stick together, falling as a mass rather than as individual beads, thus clumping in the paint film. It is not uncommon for beads to clog the dispensing equipment, which often must then be cleaned for marking to continue. To avoid clumping, beads can be moisture-proofed by adding a small amount of absorbent powder, such as china clay, or by coating the beads with a proprietary silicone-based material.

As with the gradation of beads, the proper rate of bead application for a given quantity of marking material is uncertain. It is generally agreed, however, that factors such as the size of beads, the thickness of the binder, the type of bead (flotation or nonflotation), and the expected service life of the retroreflective marking all exert an undeniable influence on optimum rate of application. Numerous research studies involving both field and laboratory tests have addressed the effect of each of these factors in terms of durability and cost-effectiveness.^(12,13)

Prismatic Cube-Corner Retroreflection

The most common use for prismatic cube-corner retroreflection is in raised pavement markers (RPMs). Prismatic sheeting is also used for retroreflective buttons for post-mounted delineators. For simplicity, this discussion will concentrate on the use of prismatic retroreflection in RPMs.

Physical Description

Raised pavement markers (RPMs) come in a variety of configurations, some with the characteristic wedge shape, some round or oval markers, markers with and without replaceable retroreflective inserts, and so on.

A more complete review of the physical characteristics of RPMs is found in chapter 7.

Most retroreflective RPMs employ prismatic cube-corner reflectors to achieve the necessary retroreflective properties, but some also use glass beads. Glass beads used in RPMs function in much the same way as those for pavement markings, except that the bright spot created by the beads' focusing effect is diffusely reflected by the RPM's plastic housing, or base layer of the retroreflective element, instead of the pigments in the paint binder. Since the physical characteristics of retroreflection of glass beads have been discussed in the previous sections, the following discussion will focus on prismatic cube-corner retroreflectors and their use in RPMs.

Retroreflective Properties

Prismatic retroreflection of RPMs is achieved through the use of many tiny cube-corner retroreflective elements in an insert or retroreflective sheeting on the face of the marker. Each element is a tiny half-cube, open in the direction of the driver. When a light ray enters the cube, it bounces off each mirrored face of the cube-corner element. The beam's directional component perpendicular to the plane of the surface is reversed. Eventually, all three components of direction have been reversed, and the exit direction of the light ray is nearly equal, but opposite, to that of the incident light ray. (See figure 14.)

Laboratory measurement of retroreflection of RPMs is similar, but simpler, than for pavement markings. Each marker tested will have definite area and geometry in each test, which will probably be more consistent between different testing agencies. The ASTM standards originally were written with the intention that they be used for testing retroreflectors of finite area with a fixed test geometry. The geometry and area must be constant to ensure

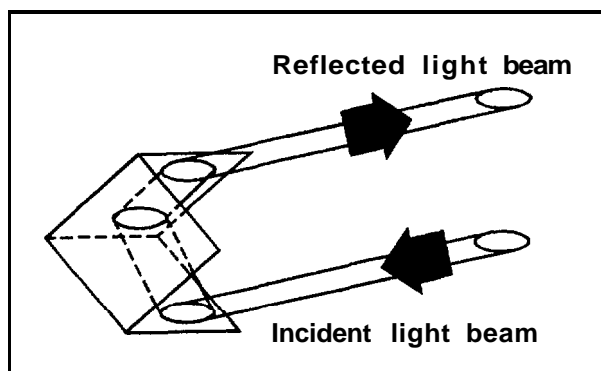


Figure 14. Prismatic cube-corner retroreflection

consistent results for coefficients of retroreflection.

Figure 15, taken from the *Standard Practice for Describing Retroreflection* (ASTM Standard E808-91), illustrates a method of testing retroreflection that is naturally compatible with laboratory testing of RPMs or their retroreflective inserts.⁽⁸⁾ The figure again makes it clear that the test methods were not developed with pavement markings as a primary consideration. Care should be exercised not to compare results for coefficient of retroreflection for RPMs to coefficient of retroreflected luminance, R_L , for pavement markings. These coefficients are measured differently; results will not be consistent.

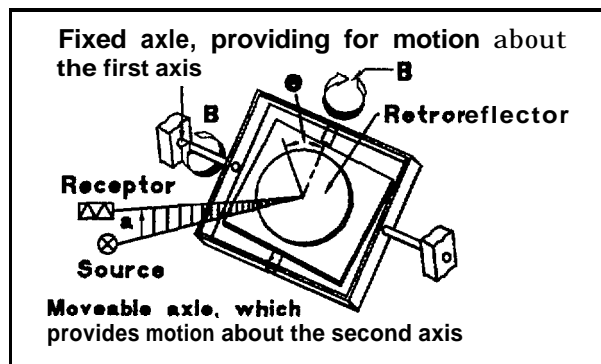


Figure 15. Retroreflection test geometry

Though the standards are suited to measurement in the laboratory of RPMs' retroreflectivity, there is still difficulty with field measurements. There are numerous problems with creating a device that will measure the retroreflectivity of RPMs in the

field because of the need for collimation and problems with placement and light exclusion.

One erroneous method that is often used by researchers and highway agencies entails simply measuring the distance at which RPMs are visible under the illumination of standard automobile high-beam headlights. This method is discouraged because drivers seldom drive with high beams, and the results for visibility distance are very misleading. There is little evidence that correlates performance of RPMs under high-beam illumination to their performance when viewed using low beams.

The main problem with the retro-reflective performance of RPMs is how quickly their performance is degraded. Van Gorkum states that markers, on average, lose 95 percent of their retroreflectivity in the first six months of use.⁽¹⁴⁾ However, much of this loss is recovered during periods of wet weather when water fills in surface scratches on the face of the RPMs. More information on retroreflectivity problems with RPMs and possible solutions is given in chapter 7.

QUALITY ASSURANCE

One of the problems with pavement markings is their inconsistency. Highway agencies cannot reliably predict performance. Some of the methods that have been instituted to remedy inconsistency and ensure quality of materials are discussed in the following sections.

Vendor Certification

Vendor certification for marking materials is of increasing concern. Retro-reflective performance is probably the main barometer of overall effectiveness of pavement markings. However, it is difficult to test, as well as costly to implement testing for all markings applied.

Many State DOTs now maintain a list of “prequalified” vendors. Prequalification is accomplished through procurement and testing of many different vendors’ products on a regular basis, and keeping a list of those vendors whose materials can be relied upon to perform well. An improved marking system is obtained, less rigorous pavement marking inspection is required, marking uniformity is increased across the State, and, it is hoped overall cost-effectiveness is achieved.

Procurement

To maintain a comprehensive list of qualified vendors, a variety of vendors, products, and marking materials must be sampled. Therefore, the procurement of materials to be tested is an important process. Obtaining a variety of materials to test can be costly. Sources must be reviewed carefully so that only promising vendors and materials are selected to minimize waste of time and money.

Testing

After a list of potential sources is created and samples obtained, tests must be conducted on the material’s performance. Evaluation usually consists of both laboratory tests and field tests of actual performance.

Laboratory testing consists of chemical and other types of testing to be sure that the materials used meet State specifications for composition, brightness, resistance to gelling and caking, and so on. Each State normally has some type of materials or chemistry laboratory where those tests can be performed.

Each State also will normally have a paint test facility where markings are painted on the road and observed for durability and visibility. Often these markings are painted transversely so that wear is accelerated. There are correlative equations to compensate for durability in

the wheel path versus durability of longitudinal markings.

Markings also can be tested for retroreflectivity and skid resistance in the laboratory and in the field. The results of all the tests will be collated to produce a list of vendors and products that meet State standards.

Regional Test Facilities

Procurement and testing can be expensive and time-consuming. A program has been initiated to develop regional test facilities so that States within that region will not perform redundant testing.

Regional test facilities have the responsibility of performing testing and specifications writing to be used by all the States in their respective region. The number of regional test facilities should be large enough that the conditions in each region would be similar for all its component States with regard to delineation needs, climatic characteristics, and price of materials and contractors. Two regional test facilities have been established, one in the Northeast and one in the Southeast.

In the Northeast, there is a single test facility, established by the Northeastern Association of State Highway and Transportation Officials (NASHTO), which resides with the Pennsylvania Department of Transportation (PennDOT). NASHTO does not now maintain its own list of prequalified vendors, but it cooperates with 11 other Northeastern States to test possible material sources for use by all.⁽¹⁵⁾ The facility is located in the PennDOT materials testing laboratory, keeping costs at a minimum. PennDOT acts as an organizing force to coordinate and collate testing efforts throughout the Northeastern States. It was funded initially in part by a FHWA contract on testing of pavement traffic marking materials.

The Southeastern Regional Test Facility (SRTF) was created by a Southeastern Association of State Highway and Transportation Officials (SASHTO) Ad Hoc committee in 1988 with the objective of organizing the States' separate material testing efforts.⁽¹⁶⁾ The SRTF differs from the NASHTO facility in that it has no central location. Rather, it is simply an organization of existing highway personnel, buildings, and equipment within the SASHTO region. Of the 12 SASHTO States, 11 are currently involved in some type of material testing for the program. By combining the States' resources in this manner, the program encourages cost-effectiveness for the participating States. It also creates a uniform marking system throughout the participating States. One problem with pavement marking systems in the past has been inadequate technology transfer between highway agencies. Much of this has been caused by a lack of standards addressing the pavement marking issue, and the inconsistency of the standards that do exist. The wide variety of laboratory and field test methods used by States has also contributed to the problem. The regional test facility network promoted by the FHWA should alleviate these problems.

CHAPTER 3. DRIVER VISIBILITY NEEDS

INTRODUCTION

The primary purpose of a roadway delineation system is to provide the visual information needed by the driver to steer a vehicle safely in a variety of situations. The delineation technique used must define the field of safe travel, and it must be visible in daylight and darkness, as well as in periods of adverse weather such as rain and fog.

This chapter will discuss how to accomplish the task of providing adequate delineation, and what physical parameters, such as luminance and contrast, affect the communication of visual information. Recommendations will be made about minimum values for these parameters and visibility distances for a variety of situations. Also discussed is why visibility should be increased to its maximum level (increased brightness needed by older drivers, for example).

Finally, roadway and traffic characteristics that affect the retroreflectivity of delineation systems are reviewed. The properties of retroreflective materials (and the pavement surface) affect many of the pavement marking materials and devices. A short discussion of these variables also is included to provide the background for subsequent chapters.

Driver Visibility

The ideal form of delineation is that which provides the most guidance and warning to the driver. Research has been directed at defining the behavioral and perceptual characteristics of drivers and relating these human factors to the safety and operational efficiency of the nation's roadway system. This research has played

a major role in the development of new materials, specifications, and standards. The field of human factors research related to the driving task is much too complex to be included as part of this Handbook. This discussion is limited to a summary of driver characteristics that influence the design and installation of delineation systems.

Generally, the ability of the driver to operate a vehicle safely is based on the driver's perception of a situation, level of alertness, the amount of information available, and the driver's ability to assimilate the available information. The driver's tasks are the following:

- Control; the physical manipulation of the vehicle. By this overt action, the driver uses the steering wheel to maintain lateral and longitudinal control of the vehicle.
- Guidance; the selection of safe speed and path. In this decision process, the driver must first evaluate the situation to determine the speed and path appropriate to existing conditions. Then the driver must translate these decisions into control actions (lane positioning, headway, passing, and so on).
- Navigation; the planning and execution of the trip, from origin to destination.

Of these three tasks, failure in control has the most severe consequences of accident potential.

Older Drivers

In addition to the stringent requirements for delineation created by the general populace, there are individuals whose

visibility needs are even greater. These include persons with reduced or impaired vision, color vision deficiencies, or those driving under the influence of intoxicants. But perhaps the most important group is drivers 55 years and older. This group is the most rapidly growing segment of our country's population and there is significant research indicating that they need improved visibility on highways.

A recent study for the Transportation Research Board gives a quantitative measure of the difference in visual capability due to age.⁽¹⁷⁾ The report defines *threshold contrast* as the minimum difference between luminance of a target and the luminance of its background for detection. In figure 16, the threshold value for a 65-year-old is seen to be an average of about twice the value for a less than 23-year-old.

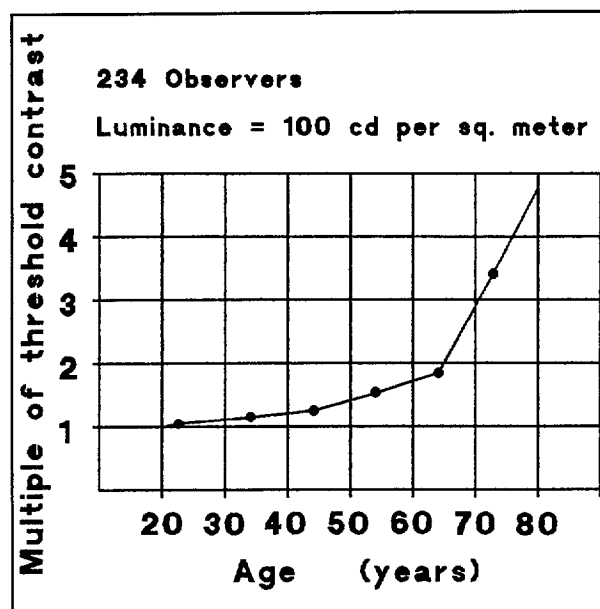


Figure 16. Threshold contrast requirements as age increases

Mace showed that a driver's perception-reaction time continually increases with age.⁽¹⁸⁾ This means that the minimum required visibility distance for older drivers also increases with complexity of decisional tasks. These changes are caused by the decreased cognitive abilities and psychomotor skills associated with advanced age.

In terms of roadway delineation, these demands require the use of brighter delineators to increase visibility distances and additional types and amounts of delineation to increase available information.

For these reasons, highway marking, signing, and other safety features provided for roads may not work adequately for all ages of drivers. In some cases, drivers aged 65 and older may require four times as much light to see as well as a 39-year-old. Also, evidence supports the fact that older drivers adopt a less flexible searching strategy. They look at fewer items in the roadway in a given time than do younger drivers. It is important to provide older drivers with more redundant and brighter forms of delineation. Recommended delineation treatments to supply older drivers the visibility they require include such enhancements as 8-inch (20-centimeter) edgelines, special posts for post-mounted delineators, and improved retroreflectivity to increase the brightness of pavement markings and their contrast with the pavement.

VISIBILITY CRITERIA

Several criteria determine delineation visibility. These criteria are used in a similar manner to those for traffic signs. The following discussion of these criteria is derived from a FHWA research program concerning visibility of highway signs.⁽¹⁹⁾

Luminance

Luminance, in the context of delineation visibility, is the total amount of light the driver receives from a marking. As shown in figure 17, light from automobile headlights is retroreflected by the marking back in a cone around the direction of the headlights. Luminance of the marking is directly proportional to the amount of this light energy that is directed toward the driver's eyes.

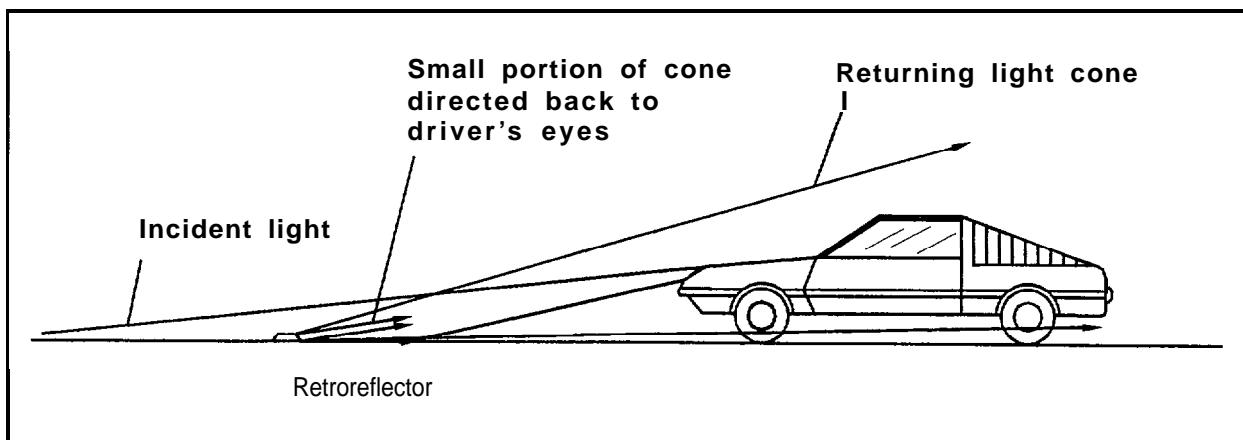


Figure 1'7. Light return by pavement markings

Contrast

Contrast is the ratio of luminance from the marking to luminance from its surroundings, measured from the driver's position. Much more important for overall visibility than luminance, contrast tells how clearly a target stands out from its background. Therefore, contrast is a much better measure of a marking's visibility.

Conspicuity

Conspicuity refers to the likelihood that a driver will notice a certain target at a given distance. It is probably the best measure of visibility, but also the most difficult to quantify. Unlike luminance and contrast, conspicuity is not a simply determined optical quantity. It is dependent on a variety of factors, many of them unpredictable.

Conspicuity is probably more related to contrast than to luminance, since contrast defines how easily an object can be seen against its background. Unfortunately, it depends also on the driver's capabilities, mood, and degree to which the target is expected. It also is directly related, but in a cryptic manner, to the visual complexity of the scene that the driver views.

Like many of the other conspicuity factors, visual complexity is an enigmatic

phenomenon. It is difficult even to determine an estimate for the conspicuity factors and very difficult to combine them in a way that will yield a numerical measure of conspicuity. Conspicuity is a quantity that can be tested only empirically.

However, Schwab and Mace researched the effects that a complex background has upon sign visibility.⁴⁴ Those interested in the methods of this research may refer to the original work.

Legibility

Legibility refers to the probability that a driver will understand the message that delineation is meant to convey. It is an even less tangible quantity than conspicuity.

Legibility relies upon a nearly infinite number of factors, few of which are well-understood. Further, the criteria by which legibility may be judged differ for different types of delineation.

In the field of highway signing, empirical relationships have been found for legibility based on such variables as character height, color, spacing, and stroke width. These same criteria apply to such forms of delineation, including Chevron, Large Arrow, Turn and Curve signs, etc.

These variables have little or no meaning, however, when applied to pavement markings or raised pavement markers (RPMs). For these types of delineation, it may be much more important that they have sufficient contrast with the pavement, are consistent with other similar markings, and do not conflict with other types of delineation or signing nearby.

PAVEMENT MARKING VISIBILITY DISTANCE

Visibility distance refers to the range at which a marking can be seen. It does not guarantee that a given driver will actually notice the marking or correctly perceive its meaning. Those actions are related to conspicuity and legibility. Visibility distance specifies only the distance at which a given driver is *capable* of seeing a marking.

Since visibility distance does not incorporate human reaction into its definition, it is quantifiable and is directly dependent on the luminance and contrast of the marking and on the contrast sensitivity of the driver.

Driver Events

In highway signing, minimum visibility distance is determined by certain driver events. The visibility distance must be large enough for all the driver events to occur before the information conveyed by the sign must be acted upon.

Delineation markings are different from highway signing because markings convey a continuous message. However, delineation is similar to highway signing because visibility distance of pavement markings is vital for giving ample warning of changing roadway alignment. Based on the driver events that must occur for signing, the following driver events apply to delineation:⁽¹⁹⁾

- Detect change in delineation (turn, curve, freeway exit ramp).

- Recognize message that delineation conveys.
- Decide appropriate reaction.
- Initiate response.
- Complete vehicle maneuver.

Adequate visibility distance will provide the driver sufficient time to perform all of these actions.

Guidelines for Effective Delineation

A 1988 FHWA study combined use of computer simulations, observational field studies, and laboratory experiments to determine requirements for effective delineation.⁽²¹⁾ Two conclusions were reached about the preview distance that delineation should provide.

First, delineation should provide a minimum of 2 seconds of preview distance for short-range guidance in extreme situations. This value agrees with that established by Allen for short-range visibility distance.⁽²²⁾ This value applies to extreme situations, including heavy rain or fog or glare from opposing headlights. Preview distance is important because the view of the road ahead is very limited, forcing drivers to rely on roadway and traffic information that is visible from only a short distance. The driver must respond quickly to perceived hazards or changes in alignment, making frequent steering and speed changes to correct for errors. Driver response requires heightened attention and concentration on brief glimpses of delineation from one moment to the next. The visibility distance to the delineation must provide sufficient time for the driver to detect it, recognize the roadway features and alignment ahead, and respond with steering and speed adjustments. A preview time of 2 seconds has been found to be the safe minimum acceptable limit. At 25 miles per hour (40 kilometers per hour), delineation must be visible at least 75 feet (25 meters) ahead; at 55 miles per hour (90 kilometers per hour), delineation must be visible at least 160 feet (48 meters) ahead.

Surface pavement markings typically are adequate to provide these visibility distances.

Second, delineation should provide a minimum of 3 seconds of preview distance so that drivers are provided long-range guidance information. This value agrees with that established for long-range delineation in earlier research done by Godthelp and Riemersma.⁽²³⁾ When drivers are provided 3 seconds or more to view delineation, the task of guiding the vehicle is substantially easier. The driver is no longer constantly making rapid compensations for guidance errors, but can rely more on roadway information farther ahead. Long-range information enables well-learned and more automatic driving skills that result in smoother steering and speed control. At 25 miles per hour (40 kilometers per hour), delineation must be visible at least 110 feet (34 meters) ahead; at 55 miles per hour (90 kilometers per hour), delineation must be seen at least 250 feet (76 meters) ahead. RPMs or PMDs are usually needed for this length of visibility distance.

VISIBILITY PARAMETERS

There are a number of parameters that limit delineation visibility. The first category, physical parameters, are created by limits of the driver's sensory perception. A particular driver's sight and hearing are capable only of perceiving a certain threshold of sensory phenomena. An important concern when designing delineation systems is how adverse weather and other conditions decrease the stimuli available for the driver.

The second category of parameters limiting delineation visibility, psychophysical parameters, are the limitations of driver performance created by the driver's own limited ability to assimilate and understand the available stimuli that his senses are capable of perceiving.

Physical Parameters

Visual perception is critical to the driving task. To be effective, pavement markings must present the appropriate visual clues. As a basis for vehicle control, the ability to see and perceive is a function of contrast between background and the roadway, particularly at night. The need for contrast decreases with greater background luminance; therefore, there is better detection in daylight. During clear daylight hours, visibility presents little problem because visual information is indirectly available from roadway features and surrounding terrain; hence, delineation is less important to the driving task. At night, these indirect delineators are less effective and the motorist must rely on pavement markings to perceive a safe route of travel. Long-range visibility is restricted when contrast and luminance are reduced. Rain and other adverse weather conditions further degrade the visibility of delineation to the driver.

Recommendations for Physical Parameters

Because visibility is crucial to the driving task, significant research has been devoted to defining minimum values for physical parameters that will result in adequate visibility. Freedman and associates concluded that delineation should provide a minimum luminance contrast of 1.0 for drivers to have adequate visual guidance when there is glare on dry pavement surfaces.⁽²¹⁾ Analytical studies indicated that under ideal conditions, a contrast of 0.5 is necessary for the average driver. However, conditions are seldom ideal. In fact, wet pavement conditions can become much worse than dry glare conditions. A study at the University of North Carolina showed the importance of retroreflection for wet night visibility.⁽²⁴⁾ The minimum visibility established for dry conditions corresponded to a Mirolux reading of 93 millicandelas per lux per square meter. However, another marking would need a dry reading of 180 milli-

candelas per lux per square meter, nearly double that for the first marking, to receive an equivalent subjective effectiveness rating when the pavement was wet.

In addition, older or impaired drivers often require longer preview times. Freedman and associates recommended doubling the value for luminance contrast to account for these factors.⁽²¹⁾ Or, to achieve 3 seconds of preview distance for older drivers, or for younger drivers on wet roadways, a contrast of 2.0 to 3.0 is acceptable. For dry roadways, this can be achieved if the markings provide a retroreflectivity of 64 to 127 millicandelas per lux per square meter.

In other research, both Henry and Attaway established 100 millicandelas per lux per square meter as the minimum level of retroreflectivity on dry roads.^(25,26) A higher value for retroreflectivity is recommended to account for less-than-favorable conditions and drivers with reduced visual or psychophysical capabilities. Where such levels of retroreflectivity cannot be achieved or maintained, supplemental delineation, such as special surface markings or RPMs, may be appropriate.

Effect of Adverse Visibility

Because adequate visibility has proven to be vital to driver performance, much research has been devoted to the effect that decreased visibility will have on the driver.

Simulation experiments and field tests conducted by Allen and associates provided several insights into driver performance under adverse visibility.⁽²²⁾

First, as visibility distance is reduced, delineation configuration or pattern becomes more important. Solid edgelines, longer dashes, and shorter cycle length tend to counteract some of the effects of reduced visibility.

Second, the automobile hood restricts minimum forward view to approximately 20 feet (6 meters) ahead of the driver's position. When one marking segment disappears below the hood line before a succeeding segment is visible, steering performance becomes erratic. Delineation gap length is a key variable.

Third, longer marking segments can give some indication of road curvature even though only one segment is visible. Retroreflective RPMs do not provide curvature information unless more than one marker is visible. Thus, RPMs should be spaced more closely on curved sections. Finally, preferred speed decreases with reduced visibility or, at constant speed, steering performance degrades.

In summary, the simulation experiments indicated that steering performance is related to the combined effects of reduced visibility and delineation configuration. Thus, steering performance degrades with decreased visibility distance and with a reduction in the total amount of information available to the driver. This suggests that visibility distance and delineation configurations are important variables in the design of delineation systems.

Under good visibility conditions, drivers tend to position their vehicles somewhat to the left of the center of the lane. This is because the driver is sitting on the left and has a better view of the left side of the vehicle. This position also permits the driver to maintain a relatively constant lateral position in relation to the left lane or centerline.

The field test revealed interesting variations on this expected behavior. When delineation visibility was degraded, either by reduced contrast or by a covering film of water, the drivers shifted their vehicles' mean lateral lane positions away from the left lanelines to approximately the center of their traffic lanes. An increase in the vehicles' lateral position variation showed a

decrease in lateral control performance. Mean speed was not affected significantly except in rain conditions. In the rain, average speed reduction was about 2 miles per hour (3.2 kilometers per hour) under the worst visibility condition. Finally, speed control seemed to be unaffected generally although the vehicles' speed variability was uniformly higher in the rain.

These experiments demonstrated a systematic relationship between pavement marking contrast and the ability of the driver to constantly maintain the position of the vehicle on the travel path. The expression for this relationship may be used to predict inadvertent vehicular excursions from a traffic lane as a function of marking contrast. Thus, a relationship between contrast and accident potential can be established.

The rain experiment indicated the effectiveness of retroreflective RPMs and the inadequacy of pavement markings for guiding drivers in the rain. With only pavement markings for guidance, wet-weather drivers demonstrated a potentially dangerous combination of increasing lateral placement variability and decreasing mean distance from the laneline. At the same time, they showed signs of heightened agitation, indicating they were exerting greater effort. When they returned to a roadway section where RPMs supplemented the pavement markings, their performance recovered and their psychophysiological stress returned to normal levels. Even in dry weather, lateral position variation was lessened when RPMs were used with markings. It can not be concluded that the addition of RPMs improves driver performance under all circumstances, though it is likely that such improvement occurs.

Advances in material technology may improve the performance of pavement markings alone. The delineation research at the University of North Carolina studied the effectiveness of large glass beads for increased retroreflectivity.⁽²⁴⁾ The study

evaluated the performance of pavement marking materials under wet, nighttime conditions. Seven different marking tapes and one formulation of thermoplastic marking were evaluated under wet and dry conditions with a Mirolux retroreflectometer. According to the study, "under actual rainfall conditions in the field, VISIBEADtm (Potters Industries, Parsippany, NJ) markings gave visibility distance double or greater than visibility distances for similar lines with standard beads."

In the past, the use of these large glass beads has been restricted to materials with strong binders and resins, such as thermoplastic, epoxy, and polyester. Potters Industries has formulated a line of VISIBEADStm for use with latex traffic paint. The formulation has just completed a nine-month evaluative test in which the beads held firmly in the marking after three snowplowings.⁽²⁷⁾

These types of advances in marking technology may eventually make markings alone as good as markings with RPMs but at a lower cost.

Psychophysical Parameters

A FHWA report defines the following psychophysical parameters that affect driver performance: driver perceptual abilities, driver cognitive abilities, and driver psychomotor abilities.⁽¹⁹⁾ The field of human factors research attempts to define how these parameters affect drivers so that a more effective delineation system can be designed.

However, this Handbook will concentrate simply on empirical relationships to determine how these parameters affect performance in specific roadway conditions. By comparing performance with a variety of delineation treatments, relative levels of effectiveness can be determined. Research conducted in this manner is discussed below.

Freedman and associates made observations concerning effects of psychophysical parameters, focusing on the effect that visual complexity of a scene has on driver performance.⁽²¹⁾

Their laboratory studies indicated that in situations where few demands are made for the driver's attention, the presence of stationary roadside objects, such as lights, signs, and buildings, tends to reduce the need for high-level delineation. However, where visual complexity coexists with demanding traffic operations, high-level delineation, including more visually prominent markings, RPMs, and post-mounted delineators (PMDs) (where appropriate), are preferred by drivers.

For simulated horizontal curves on wet and dry surfaces, the combinations of markings with RPMs and markings with PMDs were associated with smoother vehicle control and better lane tracking. The presence of simulated visual complexity did not reduce driver performance. For simulated bifurcations on wet surfaces, delineation treatments containing markings and RPMs or markings and PMDs were associated with smooth vehicle control, especially where background visual complexity was high. For simulated left-turn lanes on wet surfaces, delineation treatments containing RPMs were associated with smooth driver performance, especially where surrounding visual complexity was high.

The researchers noted that current guidelines for the selection of delineation treatments do not account for visual complexity of the surroundings.

The results of the laboratory tests agreed with results from the researchers' observational field study on a horizontal curve. Markings compared to markings with RPMs, PMDs, and chevron signs produced findings similar to previous speed and lane-tracking studies. The individual effects of RPMs, PMDs, and signs could not

be analyzed separately, but their combination with highly visible pavement markings demonstrated improved lane tracking and suggested that drivers more easily obtained proper visual guidance with the upgraded delineation.

Hoffman and Firth studied visibility of pavement markings.⁽⁶⁾ They found that instrument readings for retroreflectivity corresponded linearly with observers' ratings of appearance of markings if plotted on a logarithmic scale. (See figure 18.) This finding suggests there is an optimal value, near the break of the curve, after which increasing retroreflectivity will do little for increasing visual performance.

Hoffman and Firth also noted that a marking's visual performance was not a function solely of its retroreflectivity. Their studies confirmed that a wider marking of lesser brightness can be just as visible as a narrower marking of greater brightness. Therefore, it is necessary to examine all options and match a delineation system with all aspects of the roadway and application equipment, including marking width, color of pavement, climatic characteristics, pavement substrate type, and marking cost.

In light of these findings, it is vital to adopt a "systems" approach to delineation design. Delineation effectiveness depends largely upon the complex interaction of many variables that affect visibility. Recognizing the importance of the interaction of these variables, Kalchbrenner stated: "The term 'system' implies design and synergy. Improved roadway performance and service life have been demonstrated at multiple locations in durable materials by properly sizing and treating beads for the thickness and type of binder used."⁽¹⁰⁾

In a general sense, effectiveness may be drastically increased by treating the roadway itself as a system. Consideration of factors, such as visibility demands on

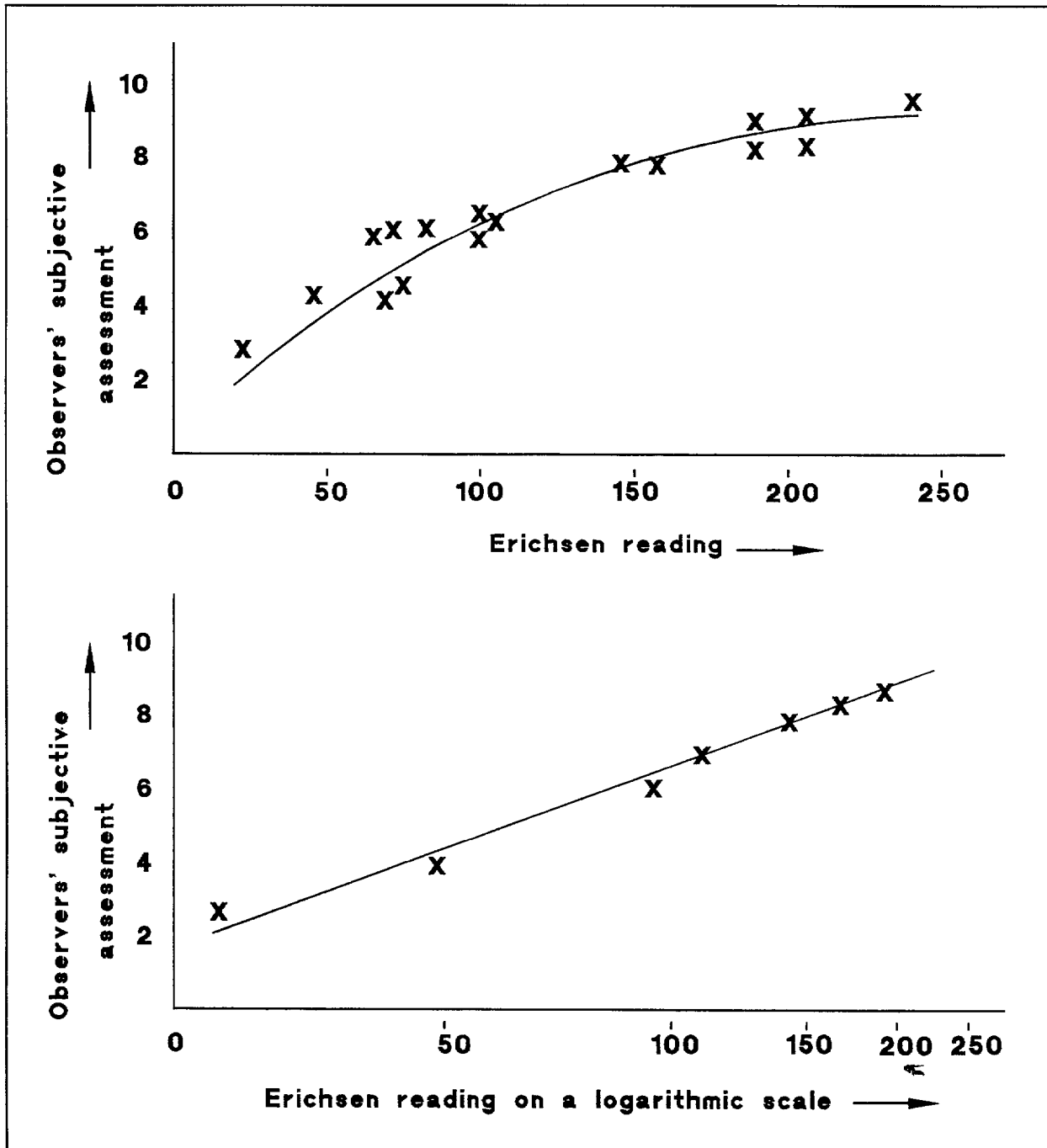


Figure 18. Subjective ratings of visibility vs. retroreflectometer readings on a linear and a logarithmic scale

drivers, pavement material, visual complexity and luminance of surroundings, and types of marking materials available and their differing properties, is critical to selecting a roadway marking system appropriate for a particular application.

DELINEATION VARIABLES

When adopting a systems approach to delineation design, key variables that should be considered in determining the most appropriate delineation treatment and technique are roadway geometry, weather

and climate, traffic volume and composition, and type of substrate. The way that these variables interact with the marking material and application technique will determine the marking's visibility and durability. A review of the significant effects of these variables follows a discussion of each variable. Detailed descriptions of the research and demonstration projects are available in the referenced reports.

Roadway Geometry

Roadway geometry has more effect on the delineation treatment than on the various delineation techniques. In this context, *treatment* refers to centerlines, edgelines, PMDs, including width, spacing, gap-to-segment ratio, and colors. *Technique* refers to the various delineation devices, materials, and application procedures.

In a definitive study of roadway delineation systems conducted by the National Cooperative Highway Research Program (NCHRP), the research centered on the following set of geometric situations: tangent sections, horizontal curves, no-passing zones, pavement width transitions, merging-diverging areas, turns, turns with deceleration and/or storage lanes, stop approaches, railroad crossings, and crosswalks.⁽²⁸⁾

Each geometric design aspect studied had a unique set of driver information needs and associated delineation requirements. These "classic" situations were used to evaluate the safety of various delineation treatments and their impact on driver behavior and traffic performance.

The study showed that areas with no previous delineation were made safer by application of standard delineation treatments. Accident rates were reduced significantly. Major changes in delineation treatments can produce measurable changes in traffic performance. However, minor variations of delineation treatments, such as spacing, gap-to-segment ratio and color, did

not affect accident rates or show significant differences in traffic performance measures. It was concluded that minor variations of delineation treatments must be judged on factors other than accident reduction.

In addition to the NCHRP research, there have been a series of before-and-after studies of the effect of edgelines on traffic performance and accident rates. In general, these studies are not comparable even though most of them concentrated on rural two-lane roads. The inability to make direct comparison was a result of the vastly different conditions that were present, such as lane width, the absence or presence of shoulders, and other environmental factors.

Nonetheless, the studies indicated that edgelines on tangent sections tend to decrease variability in lateral placement. Average lateral placement shifted away from the roadway edge. Because of the increased potential for head-on collisions inherent in shifting vehicles toward the centerline, many States prohibit edgelining pavements narrower than 18 feet (5.5 meters).

Another study showed that edgelines reduce speed through horizontal curves and minimize centerline straddling.⁽²⁹⁾

The safety and cost-effectiveness of six delineation treatments for various geometric situations was studied.⁽³⁰⁾ The treatments consisted of no delineation, centerline, centerline plus edgeline, centerline plus PMDs, and centerline plus guardrail. The study examined the effect of the various combinations of delineation treatments on mean accident rates. The more sophisticated treatments, such as centerline plus edgeline, or centerline plus PMDs, produced a decrease in accident rates.

It should be noted that some recent experience on winding and/or mountainous roadways demonstrated a driver tendency to increase speed beyond safe levels where edgelines were provided. The decrease in

head-on collisions was offset by an increase in run-off-the-road accidents. It has been suggested that enhanced guidance provided by edgeline gives the driver a false sense of security. It may result in overconfidence in the driver's ability to control the vehicle and maintain a safe position in the roadway.

Weather and Climate

Prevailing climate and weather conditions influence the effectiveness of delineation. Durability of materials and installation techniques are also influenced by weather.

During daylight hours, rain reduces the driver's ability to see the surroundings. At night, headlight glare from oncoming vehicles, windshield wiper action, and the slippery pavement surface, coupled with degraded retroreflectivity of pavement markings, makes driving particularly hazardous and difficult. RPMs and PMDs are much more effective than pavement markings in these conditions. Markings quickly lose their retroreflectivity due to surface-water film. During daytime rainy periods, RPMs do little to improve visibility, but the audible rumble when passing over the markers alerts the driver of lane straddling.

Rain does not affect the durability of pavement markings. Tire action on wet thermoplastic has been known to clean the markings. Maintenance personnel cite numerous incidents of improved visibility of thermoplastic lanelines after several hours of rain. Conversely, PMDs are subject to splashing from wet highways, which degrades their retroreflectivity. Cleaning of the retroreflective tabs may be needed.

More than rain, snow reduces the driver's visibility. Even moderate snowfall usually obliterates all pavement markings. Also, pavement markings can be damaged from snowplow activity and the use of chemicals and deicing salts. PMDs (with

extension posts where drifts are high) provide effective edgeline and roadway alignment delineation, but are vulnerable to knockdowns by snowplows.

Fog also reduces a driver's visibility. No cost-effective delineation techniques are adequate in dense fog. However, experiments with various forms of surface highway lighting have been undertaken.^(31,32) Roadway delineation has been improved by closely spaced, high-intensity, retroreflective RPMs combined with nonretroreflective RPMs to create a rumble effect when passing over the marking. Similarly, where short-range visibility is a recurring problem, the gap in a skip line has been decreased in the problem location so that at least one or two marking segments are always visible.

Like fog, blowing sand reduces the driver's visibility. It can also collect on the roadway and obscure pavement markings. The abrasive effect may damage paint and thermoplastic markings. Some agencies close highways or provide platoon escorts through areas affected by fog or blowing sand.

The reduced visibility associated with the effects of weather, such as rain, snow, and fog, makes driving difficult. In these situations, safety considerations always transcend cost-effectiveness concerns.

In addition to the physical presence of rain, snow, fog or blowing sands, or temperature extremes can influence delineation. Thermoplastic materials and some paints are often formulated to withstand specific temperature extremes. For example, a thermoplastic product formulated for the Northeast would not be applicable in the Southwest. In cold climates, the freeze-thaw cycle can cause early failures by weakening the marking's bond with the pavement surface.

Summer heat also affects pavement markings. In parts of Arizona, California, Nevada, Texas, and other States with hot

climates, surface temperatures frequently exceed 120 degrees Fahrenheit (49 degrees Celsius). Under such thermal stress, thermoplastic on asphalt pavement will “crawl,” distort, and become badly marked with tire tracks, resulting in reduced daytime visibility. However, tire tracks on the markings will not significantly affect nighttime retroreflectivity. In addition, the ultraviolet rays of strong sunlight can affect the color and life of conventional delineation materials.

Traffic Volume and Composition

Traffic volume and composition can affect the choice of delineation treatments and techniques. Traffic volume is important because average daily traffic (ADT) is often the major criterion used to select delineation techniques. For example, roadways with high-traffic density may be better served by the installation of highly durable devices, such as RPMs, hot-laid thermoplastic materials, or epoxy. These durable materials will provide long-term delineation, thus avoiding the need for frequent maintenance. They also reduce the exposure of maintenance crews to traffic and the disruption of traffic. The higher initial cost can be balanced against the safety and long-term economic benefits of the more-durable techniques.

Low ADT may indicate that painted markings alone or in combination with RPMs or PMDs are adequate and may last one or more years without repainting. States must experiment to determine the optimum periods for repainting in these locations.

Traffic composition can affect the service life of delineation materials. A high percentage of trucks, buses, and other heavy equipment can damage or wear out markings much faster than passenger vehicle traffic. For example, rural, farm-to-market, low-density roads or industrial access roadways may need more durable applications than their ADT might indicate.

Another characteristic of traffic flow that influences selection of delineation systems is location of the markings. Longitudinal markings last longer than transverse markings, and edgelines last longer than lanelines because of fewer crossovers.

As a guideline for selection, ADT is loosely correlated with service life. A graph is developed, like the example shown in figure 19. Some agencies develop more complex correlations. Rather than simple ADT, the District of Columbia uses the number of wheels crossing a point on the road as an indicator. The reasoning is that traffic abrasion occurs only when the wheels of a vehicle pass over a marking. Edgelines or heavily traveled freeway lane-lines may not experience the same wear as markings in areas with lower ADTs, but in the latter, crisscrossing or encroachment is often more pronounced.⁽³³⁾

The technique used by Washington, D.C. for calculating the expected service life as a function of traffic flow is based on several assumptions.

- Expected service life is measured by the total number of vehicles per lane that have passed over the marking when it is worn completely from the wheel paths.
- Wear of pavement marking materials is a function of the second power of the number of vehicles per lane passing over the materials laid normal to the direction of traffic flow.
- Service life is a measure of the number of vehicles per lane that have passed over the material when the marking is no longer serviceable on account of having lost its luster, lost its retro-reflectivity, or of having been worn completely from the surface in the wheel paths.
- Markings of conventional traffic paint or other quick-drying materials should be renewed when material in the wheel

paths has been worn to half its original area. It is approximately at this point that the marking can be expected to lose its luster, and beads to lose their retroreflectivity.

- Thermoplastic markings retain brightness and beads and are still retroreflective until all the material in

the wheel paths has been worn away from the pavement.

- Cost-effectiveness is the ratio of the cost per linear foot of marking to service life. The service life is expressed in millions of vehicles per lane of traffic.

This technique appears to work well for high-density facilities. Whether simple or sophisticated correlations are developed depends on the type and function of each specific site. Different traffic characteristics for a site can greatly affect service life. Traffic characteristics are important when judging the cost-effectiveness of the more durable delineation techniques.

Substrate Material

Variations in type and condition of the substrate determine, to a large extent, the durability and visibility of the pavement marking. The substrate materials upon which pavement markings are applied fall into two categories: asphaltic concrete (AC) or Portland cement concrete (PCC). *Asphaltic concrete* denotes a dense-graded road surface made of hot mineral aggregates plant-mixed with hot asphalt. *Bituminous concrete* includes both asphaltic concrete and similar mixtures made with refined tar. The coarse aggregate is generally crushed stone, crushed slag, or crushed gravel. Sand and filler or sand only is usually added. Bituminous concrete has the advantage that it can be driven on immediately after construction.⁽³⁴⁾

Another form of asphaltic concrete is *open-graded*, which uses only coarse aggregate. When applied as a surface course, it has a high porosity and permeability, as well as a rough surface texture. The porous feature minimizes the potential for hydroplaning by allowing numerous escape channels for water beneath a moving tire. Water ponding prevents markings from retroreflecting incident light. Therefore, use of open-graded asphalt

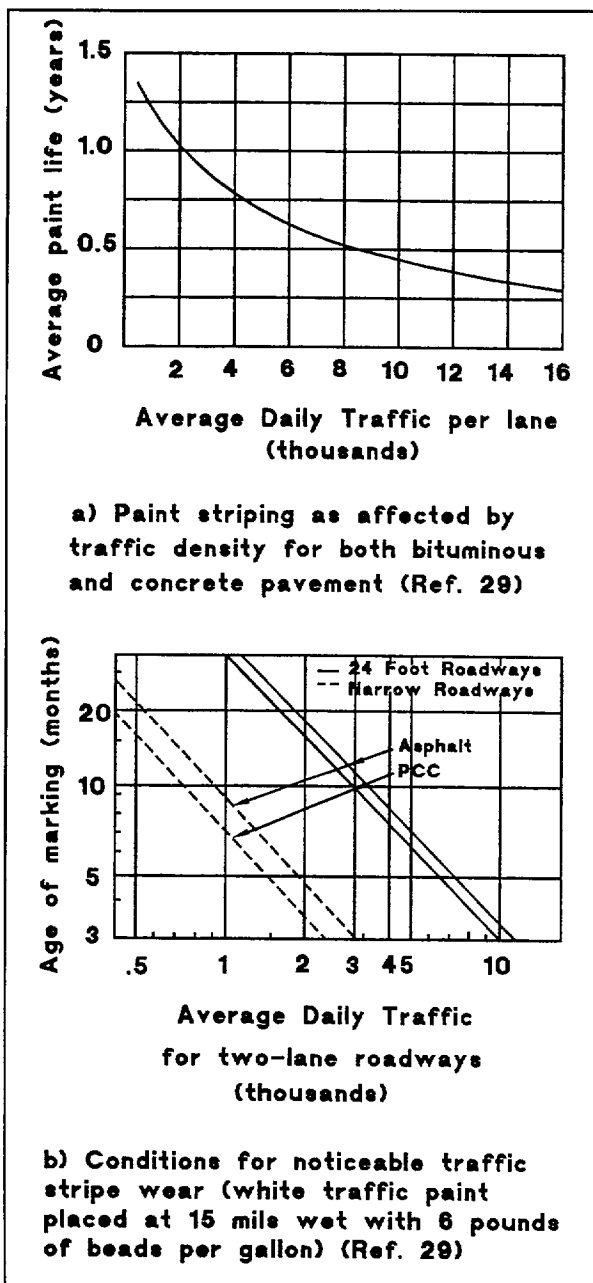


Figure 19. Effect of ADT on service life of thermoplastic markings

minimizes the time during a rainstorm that the delineation is ineffective.

Portland cement concrete consists of a relatively rich mixture of Portland cement, sand, coarse aggregate, and water. It is laid as a single course. When properly designed and constructed, it has a long service life and relatively low maintenance requirements. A minimum of five to seven days curing time is required before the pavement is ready to be driven on.

Because the service life of AC is dependent on so many variables (for example, type of aggregate, type of base, traffic density, climate conditions), an average value for expected service life is of little value. In general, PCC pavement will last about twice as long as AC. PCC is much smoother than AC. The PCC often is scored or treated to increase its skid resistance.

The life of pavement is significant particularly when considering the application of long-term delineation. For example, RPMs or thermoplastic markings could outlive an aging AC surface under certain circumstances. The high initial cost of these treatments is justified by their durability and longevity. Since imminent resurfacing or reconditioning of AC pavement cancels out this advantage, alternate methods should be considered for the interim period.

Greater quantities of paint or hot-applied thermoplastic materials are required with the open-graded AC pavement surface because of its porous nature. However, such a surface provides better wet-night visibility. With RPMs, the problems in obtaining a secure bond with the rough surface results in a higher percentage of dislodged markers.

Implication of Variables

The ideal form of delineation is that which performs best based on driver

behavior, safety, free movement of traffic, and cost. Various marking and delineation techniques may be used individually or collectively as appropriate.

The advantages or disadvantages of each of these techniques and treatments and their general characteristics are described in the following chapters. Highway designers must be knowledgeable in this area in order to specify economical, effective delineation.

The selection and purchase of delineation techniques and materials is a recurring activity for highway agencies. There is no universal delineation configuration that equally serves all needs. To achieve the best balance among driver requirements, safety aspects, and economic considerations, each of the variables discussed must be assessed to determine its impact on effectiveness. The following chapters place current practices in perspective and clarify the rationale used in the decision process.

CHAPTER 4. TRAFFIC PAINTS

INTRODUCTION

The use of painted markings on the roadway surface to divide the traffic stream and provide guidance to the driver has existed since the dirt road gave way to the paved road. Today, painted markings used alone or in combination with other devices comprise the most commonly used delineation technique. This chapter covers the various uses, materials, equipment, installation procedures, and other factors associated with painted pavement markings.

TYPES AND APPLICATIONS OF PAINTED MARKINGS

Painted markings are classified as either longitudinal or transverse. They provide positive guidance by defining the limits of a driver's field of safe travel, such as lanelines, centerlines, edgelines or crosswalks, and stop bars. They also provide negative guidance, which defines where drivers are not permitted to travel, such as gore areas, islands, and painted medians.

The specific application of standard colors, widths, patterns, and placement are defined in the *Manual of Uniform Traffic Control Devices (MUTCD)*.⁽¹⁾ Some basic concepts are addressed in this Handbook, but the *MUTCD* should be consulted for more precise installation information.

In addition, table 2 presents definitions of the basic types of pavement markings. This includes guidelines for selecting the physical characteristics of a marking depending on the purpose of its application.

Figure 20 illustrates basic patterns and colors that are used in a variety of common roadway situations.

MATERIALS

Conventional traffic paint continues to provide the nucleus of the nation's roadway delineation system. Continual improvements have been made in paint composition and application techniques to provide increased cost-effectiveness. A number of factors interact to determine the performance of the various types of traffic paint.

Any discussion of the materials used in painted markings must consider the three interactive elements of the paint system: the paint itself (pigment and binder), beads (retroreflective glass spheres), and pavement surface (substrate). For example, different paints react differently on asphaltic and concrete pavements. Glass beads reflect differently depending on the binder used, its thickness, and percentage of pigment.

The following background on painted markings will provide the substance for a subsequent discussion of the major factors that influence selection of a good paint for a given situation. It includes a review of the categories of paint, essential properties, and performance criteria. The use of glass beads to create retroreflective pavement markings is discussed in chapter 2.

Categories

There are several ways to classify paint. It can be classified by retroreflectivity, that is, whether glass beads have been added for nighttime visibility. Paint without beads

Table 2. Types of pavement markings

DESCRIPTION	COLOR	WIDTH	APPLICATION
Single Broken	White	4 in (100 mm)	Separation of lanes upon which travel is in the same direction, with crossing from one to the other permitted, i.e., lane lines on permanent multilane roadways.
	Yellow	4 in (100 mm)	Separation of lanes upon which travel is in opposite direction, and where overtaking with care is permitted; such as centerlines on a-lane, P-way roadways.
Single Solid	White	4 in (100 mm)	Separation of lanes, or of a lane and shoulder, where lane changing is discouraged; such as lane lines at intersection approaches, right edgelines.
		6 in (150 mm)	Lane lines separating a motor vehicle lane from a bike lane.
		8 in (200 mm)	Delineation of locations where crossing is strongly discouraged; such as separation of special turn lanes from through lanes, gore areas at ramp terminals, paved turnouts.
Double Solid	White	4-4-4 in'	Separation of lanes upon which travel is in the same direction, with crossing from one side to the other prohibited; such as channelization in advance of obstructions which may be passed on either side.
	Yellow	4-4-4 in*	Separation of lanes upon which travel is in opposite directions, where overtaking is prohibited in both directions. Left turn maneuvers across this marking are permitted. Also used in advance of obstructions which may be passed only on the right side.
Solid plus Broken	Yellow	4-4-4 in*	Separation of lanes on which travel is in opposite directions, where overtaking is permitted with care for traffic adjacent to the broken line, but prohibited for traffic adjacent to solid line. Used on 2-way roadways with 2 or 3 lanes. Also used to delineate edges of a continuous left turn lane-solid lines on the outside, broken lines on the inside.
Double Broken	Yellow	4-4-4 in"	Delineates the edges of reversible lanes.
Single Dotted	Either	4 in (100 mm)	Extension of lane lines through intersections. Color same as than of line being extended. Also used to extend right edgeline of freeway shoulder lanes through off-ramp diverging areas in problem locations.
	White	8 in (200 mm)	Separation of freeway through lane and auxiliary lane or exit lane.
Transverse	White	12 in (300 mm)	Limit lines or STOP bars; also crosswalk edgelines (minimum 6 feet [1.8 meters] apart) when not in the vicinity of school grounds.
	Yellow	12 in (300 mm)	Crosswalk edgelines contiguous to school buildings and grounds; also optional for crosswalk edgelines located within 600 feet (183 meters) of school buildings or grounds and, under special circumstances, within 2,800 feet (854 meters).
Diagonal	White	12 in (300 mm)	Crosshatch markings, placed at an angle of 45 degrees, 200 feet (61 meters) apart, on shoulders or channelization islands to add emphasis to these roadway features.

* 4-4-4 in indicates width of stripes and gap between them. Metric equivalent is 100-100-100 mm.

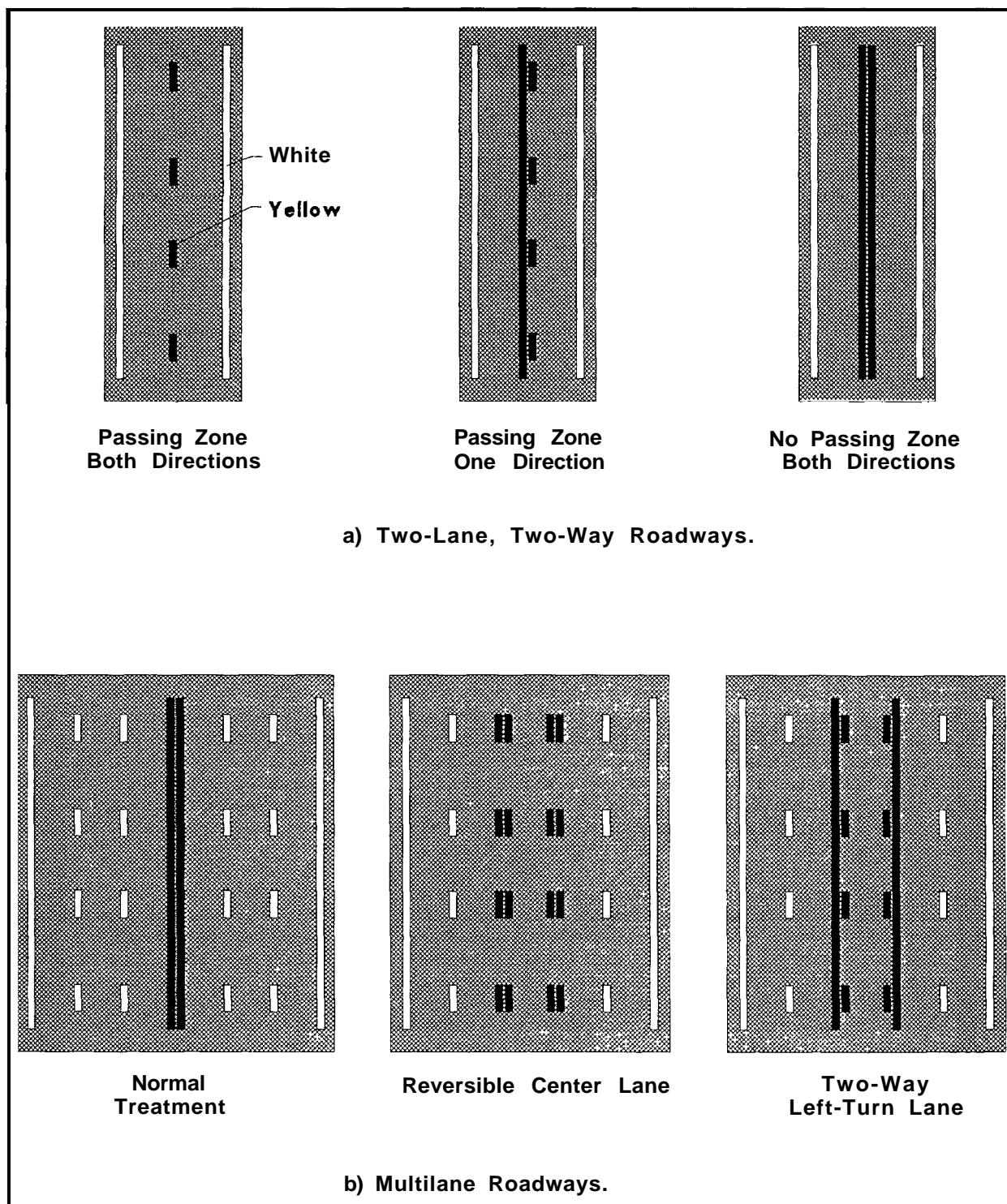


Figure 20. Typical applications for longitudinal roadway delineation

generally is used for markings not requiring night visibility, such as parking spaces and curbs.

Paint can be classified by whether it is cold-applied or hot-applied. The temperature at which paint is applied has a direct relationship to drying time which is the

third method of classification. Drying time is influenced by the atmospheric dew point, the paint's chemical composition, the temperature of the paint and pavement during application, wind velocity, and paint thickness.

The categories of paint based on drying time are defined as follows:⁽³⁵⁾

- *Conventional.* Cold-applied paints with a standard value of viscosity. They require more than 7 minutes to dry.
- *Fast Dry.* Hot-applied paints that dry to a no-track condition within 2 to 7 minutes.
- *Quick Dry.* Hot-applied paints that dry to a no-track condition within 30 to 120 seconds.
- *Instant Dry.* Hot-applied, heavy-bodied paints that dry in less than 30 seconds.

Types

The three main components of paint are binder (base material), pigment (for color and retroreflectivity), and solvent. While in containers, paint maintains its liquid form because of the solvent. When applied to pavement, the solvent evaporates, leaving a hard film. Paint is sometimes classified according to the base material used in the paint composition. The base material also is vital to a paint's drying time. Some commonly used base materials are oil (alkyd resin), oleoresin (modified alkyd, drying oil [dispersion] varnish), rubber base (chlorinated rubber), and water.

In this chapter, we will also briefly discuss some aspects of the environmental impact of the use of traffic paints. The high Volatile Organic Compound (VOC) content of traffic paints employing aliphatic and other thinners has resulted in increased use of water-based latex paints in recent years.

Alkyd and Modified Alkyd Paint

The alkyd and modified alkyd paints are generally the cheapest and fastest-drying of common materials. Experience shows them, however, to be the least durable. Though there have been attempts to increase their durability through formula variations, these usually are achieved only at the cost of increased price and/or drying time.

Alkyd paint is the workhorse material normally referred to as traffic paint. It is the most widely used material, and its lack of durability (less than three months in harsh conditions) has given rise to the development of the numerous new technologies.

Chlorinated-Rubber Paint

Chlorinated-rubber paint is an experiment into varying the base materials for paints to increase their durability. This material became available around 1964. One of the major users of this type of paint is the Texas DOT, which switched to the use of chlorinated rubber in 1966. At that time, the State was displeased with the long no-track times for alkyd traffic paints. Recently, Texas DOT has switched paints again, this time to a formulation of chlorinated polyolefin that is similar to chlorinated rubber. This material is often still referred to as chlorinated rubber.

The State has been pleased with the performance of this material, though environmental concerns with its use have created plans for the State to switch to water-based latex paints in the future. Currently, the chlorinated polyolefin is applied by the State's maintenance forces at a cost of 6 to 7 cents per linear foot. Durability is approximately 1.5 times that of standard alkyd traffic paints, with 1- to 2-minute no-track times.

The New York State DOT is another major user of this type of paint. In 1987, 90,000 gallons of the paint were applied as part of a research project.⁽³⁶⁾ The NYSDOT's goal has been to achieve a paint system that will provide year-round durability at a price similar to its current modified alkyd paint. Though not all the installations in 1987 lasted 12 full months, all lasted at least nine months, including a winter season.⁽³⁶⁾ This is about three times longer than the standard paint would be expected to last under similar conditions.⁽³⁷⁾

The only problems cited with the chlorinated rubber paint were its drying time and odor. The methyl ethyl ketone (MEK) solvent in the paint is strong, with an olfactory detection threshold about eight times lower than that of the toluene normally used in alkyd traffic paints.⁽³⁸⁾ However, chlorinated rubber paint does not appear to pose any more of a hazard to workers since concentrations are approximately equal.

Chlorinated rubber paint has a drying time of 3 to 6 minutes. NYSDOT personnel found that this could be reduced to about 1.5 minutes by varying application temperature and pressure. These no-track times, which are still longer than times for modified alkyd paint, may make the application of the chlorinated rubber paint impractical in areas with high traffic volumes or complex traffic patterns.

Water-Based Latex Paint

One type of paint that is constantly experiencing increased usage is latex paint. More importance has been placed on the environmental considerations involved in the use of traffic paint. Alkyd paints, and any other materials employing toluene or similar thinners as a solvent, release volatile organic compounds (VOCs) into the atmosphere when they are used. As a result, State highway agencies are mandating the use of VOC-free paints, such as latex formulations, on their roadways.

Specific concerns related to performance, application, and maintenance of water-based latex paints are examined in detail with other marking materials in chapter 8.

Essential Properties

In general, there are two criteria by which paint performance is judged: durability and visibility. Durability involves service life of the painted marking. This is measured as the amount of material remaining on the pavement surface over time. Visibility relates to brightness of the material, particularly at night. These properties are described by the American Society for Testing of Materials (ASTM) Standard D-7B-66T.⁽³⁹⁾

Drying time also is a major performance consideration. Faster-drying paints reduce coning for an extended drying period, decrease the exposure of the paint crew to traffic, and lessen the disruption to traffic. Other requirements typically included when specifying traffic paint are:

- *Before Application.* Paint should be chemically stable with an adequate storage life. It should maintain a constant viscosity, and be able to resist caking, settling, gelling, skinning, or color changes.
- *During Application.* The paint should adapt easily to application by commercial marking equipment. Clean-up should be kept simple. It should have a strong wetting action to permit penetration of a contaminated substrate, such as by dirt, oil, or sand. This will help provide good adhesion.
- *After Application.* The paint should not bleed or become discolored on bituminous surfaces and should resist the chemical action of alkalis characteristic of PCC surfaces. Paint also must be able to withstand chemicals used for snow and ice control. Traffic paint must be flexible enough to expand and

contract with day and night temperature changes. It should be resistant to sunlight and water but sufficiently permeable to allow moisture to escape from the substrate.

The importance of each of these requirements may vary among highway agencies. Their degree of emphasis in the paint specification may also vary.

Additionally, formulation of the paint will be affected by the delineation variables discussed in chapter 3. As noted in chapter 3, roadway geometry affects treatment more than technique, and as such will not influence paint formulation. However, substrate, climate, and traffic characteristics should be carefully considered when selecting a paint.

Paint Formulation

The major elements of paint formulations are binder, pigment, and solvent. The binder provides bulk for the film. It is made of drying oils, resins, or plasticizer in a formula that provides adhesion to the substrate and cohesion to hold the paint together. It also provides most of the resistance properties. The pigments give opacity, color, hardness, and special weathering properties. Optimum pigment volume concentration for good durability lies in the 42- to 59-percent range.⁽⁴⁰⁾ Solvents dissolve the binder and regulate the rate of film drying by controlling the rate of evaporation. They are also associated with adjusting the film solids and with the ease of application.

Modified alkyd paints, like the paint used in New York, are probably the most common marking material. These paints are normally heated to 122 degrees Fahrenheit (50 degrees Celsius) for application. They dry to the no-track condition in 1 to 5 minutes due to fast solvent release. The hard and durable resin produces a tough, wear-resistant film. It works in extreme climates as demonstrated

by successful use in Saudi Arabia, Finland, and Brazil. Modified alkyd paints have good adhesion on asphalt, bitumen, and concrete surfaces.

Traditionally, the paint-bead combination used is on the order of 15 to 17 mil (0.38 to 0.43 millimeters) wet paint thickness with 5 to 7 pounds per gallon (0.6 to 0.8 kilograms per liter) of beads within the No. 20 to No. 100 mesh range. The FHWA recommends the use of 16-mil (0.4-millimeter) wet film thickness of paint, with 6 pounds per gallon (0.7 kilograms per liter) of applied beads.

Many States seek a retroreflective painted marking with equal performance at a reduced cost. Some agencies have tried 10 to 11 mil (0.25 to 0.28 millimeters) wet paint thickness with 4 pounds per gallon (.48 kilograms per liter) of No. 40 to No. 80 mesh beads, with good results.^(40,41,42) A number of States, including California, Pennsylvania, Colorado, and Kansas, have adopted this paint-bead combination and have reported significant cost savings and no appreciable loss of effectiveness.

Purchase of Materials

Specifications for purchasing pavement marking paint are usually written in the form of a chemical composition or performance specification. The cost and availability of some of the chemical components used in the manufacture of paint vary radically from week to week, and detailed composition specifications favored by highway agencies in the past are being replaced by performance specifications. In some cases, a combination performance-composition specification is used that indicates the percentage by weight of each ingredient by generic classification without specifying a brand name or chemical formula.

Each specification has its own unique advantages and disadvantages. One study surveyed 24 States and 15 national paint

manufacturers.⁽⁴³⁾ The majority of the States surveyed still use composition specifications, but the manufacturers favored the performance specifications.

The performance specification enables a user to realize the advantage of current paint manufacturing technology. The state of the art in paint manufacturing has progressed so rapidly that it is difficult for the engineer to understand this technology and keep pace with the paint chemist. Furthermore, manufacturers indicated that the best way to lower cost is through their own research and development technology. For example, during the 1978-79 study, the average bid price for the chemical composition specification was \$3.60 per gallon (\$0.95 per liter) for yellow and \$3.36 per gallon (\$0.89 per liter) for white paint. With the performance specification, the average bid price was \$3.15 per gallon (\$0.83 per liter) for yellow and \$2.95 per gallon (\$0.78 per liter) for white paint.

The major problem with using the performance specification is in judging performance. Most States use a point system for evaluating the paint. The method is highly subjective and depends on the opinions of the individual members of the evaluation team. During the study, values assigned to color, durability, contrast, and appearance varied in many States depending on the priorities of the specific highway agency.⁽⁴³⁾

Another disadvantage is the potential difficulty in getting suppliers to replace paint that does not meet the performance specification. This can be time-consuming and may require legal action.

The advantage of a composition specification is the assurance that the purchasers are getting a paint based on their own formulations. The development of a composition specification is normally the function of the materials or testing department of each highway agency. In this process, several different paints are applied

on asphalt and concrete pavement surfaces for evaluation. Based on the results, a composition specification is then written to ensure that the user obtains the product that gives the longest service life. Quality control testing in the laboratory is included in the specification to ensure that the product furnished is the same as was requested.

After carefully weighing the advantages and disadvantages associated with paint specification, the previously mentioned specification study concluded that, "paint purchased using performance specifications appears to result in a lower average price than paint using chemical compound specifications."⁽⁴³⁾

It also concluded that when the composition specification is used, chemical components should be reviewed annually to determine the most cost-effective composition. It is frequently possible to substitute or reduce the quality of a chemical compound without sacrificing performance or color.

Testing

The prediction of the service life of paint is a critical factor in evaluating candidate paints. Field tests of various paint compositions is time-consuming and conventional laboratory tests, such as falling sand, the Taber abrasion test, and the WeatherOmeter, do not produce the best results.

A major study has been undertaken to develop an economical and practical accelerated laboratory test to estimate pavement marking material durability.⁽⁴⁴⁾ Two conclusions emerged from this study. First, field tests can be performed to give an overall durability ranking. Second, laboratory tests can be performed to provide data that can predict field test results with a high degree of reliability. If field tests are performed in parallel with the laboratory tests, statistical methods can be

used to select the least number of tests required and provide the coefficients for predictive equations.

If field tests and subsequent regression analysis are not performed, laboratory test data for the predictive equations can be obtained from the study.

The testing and laboratory analyses to be performed can be time-consuming and costly. Furthermore, the work is essentially the same for nearly all the States. At the very least, those States that have nearly the same delineation variables, such as climate, affecting their paints would benefit if some type of technology transfer program were initiated.

The FHWA recognized these concerns several years ago when it began the regional test facility program. The concept began simply as a way to reduce the redundancy of testing. The regional test facility at the Pennsylvania DOT resulted from a FHWA contract that concerned material testing the department had been awarded. Gradually, with encouragement from the FHWA, the program began to evolve into a regional facility that all the States in the Northeastern Association of State Highway and Transportation Officials (NASHTO) Region could access.

The concept has been extended so that all the NASHTO States have begun to coordinate their efforts in the field of material testing. There are now cooperative testing programs, administrated by the central Pennsylvania DOT facility, where results of tests on different materials by separate States are shared by all.⁽¹⁵⁾

Similarly, the Southeastern Association of State Highway and Transportation Officials (SASHTO) has created an organization to promote technology transfer among its constituents' States. The SASHTO facility is a more cooperative venture, comprised simply of an

organizational plan to coordinate testing efforts of existing highway agencies' personnel.

PERFORMANCE

A great deal of attention has been paid the properties of traffic paint. This has aided research aimed at developing a paint formulation that will produce improved durability, appearance, and visibility. As a result, a number of paint families effectively meet agency specifications.

There are three reasons for evaluating the performance of paint. First, performance evaluations help assess the cost-effectiveness of painted markings compared with other forms of delineation. Second, if paint is selected, it is necessary to evaluate paint samples to determine the best product to purchase. Third, it must be known how long a pavement marking will provide adequate delineation so that repainting can be scheduled.

Research indicates that the precise composition of paint is not as important as precise application of paint. It has been suggested that "a poor paint properly applied will out-perform a good paint improperly applied."⁽⁴⁵⁾ It is also well-documented that 90 percent of all paint failures are due to the type of substrate and the condition of the surface.⁽⁴⁴⁾

Performance Descriptors

A number of terms are used by various highway agencies to describe paint performance. Some of these terms such as "service life," "expected life," "lifespan or useful life," and "paint failure," often have different meanings and should not be used interchangeably. It is difficult to define these descriptors in quantitative terms since they are normally judged on a subjective basis.

Any pavement marking deteriorates gradually with time and exposure to traffic

and weather. Highway agencies often define the service life of the marking as the time between application and the time the marking should be replaced. Hence, the service life is dependent upon the extent of deterioration that can be tolerated before replacement is necessary.

As mentioned earlier, the service lives are used to evaluate painted test markings and to compute the economy of various materials. Evaluation is based on appearance, durability, and night visibility of sample materials placed on test sections. Each of these three characteristics are rated numerically from 0 to 10. A rating of 10 indicates perfect condition and 0 represents complete failure (that is, no appreciable paint remaining). Many highway agencies assume that service life is at an end when the combined weighted ratings fall to 4 or below. This is sometimes referred to as "effective life."

It has been suggested that using a rating scale with 11 grades (0 through 10, inclusive) is somewhat cumbersome. For example, on this type of scale, the difference between 7 and 8 is so small that it is difficult to maintain consistency for different ratings. Accordingly, it might be desirable to use a rating scale with fewer grades between "perfect" and "complete failure."⁽⁴⁶⁾

Performance is a function of numerous variables, not just the paint itself. The performance of identical materials will depend on the interaction of the delineation variables discussed in chapter 3. In addition, several factors involved in the application of the material affect its performance. These reasons make it impossible to determine a quick and simple formula for service life.

Causes of Failure

The integrity of a pavement marking can suffer from at least three mechanisms: loss of substance by abrasive wear on the upper surface, cohesive failure of the paint

(within the paint layer), and/or adhesive failure at the interface with the concrete substrate.

Another possible cause of failure often overlooked is within the PCC or asphaltic concrete (AC) region just below the paint-concrete interface. Stresses that cause such failures arise from the reaction of the pavement surface to the forward forces and the weight of vehicles.^{***}

Since single stresses obviously do not cause failures, fatigue must be the mechanism. Factors contributing to loss of strength of the paint, interface, and concrete may include temperature and humidity cycling, light radiation damage, chemical attack by salt and acids (from nitrogen and sulfur oxides in the air), physical attack by solvents (such as gasoline and oil), tire studs and chains, and snowplows.

With so many possible failure mechanisms, it is not surprising that there is a wide variation in the reported performance of various types of material. It is also the reason that abrasion tests have not been completely successful in predicting the service life of painted markings.

Ranges of Service Life

Although the estimated service life of painted markings is a function of numerous site-specific variables, average daily traffic (ADT) is more commonly used than any other variable. Most highway agencies consider a reasonable target to be 6 to 12 months under "normal" conditions. Three months' service may be acceptable for roadways with very high traffic density, whereas some paints may last well more than a year on roadways with low ADTs.

The amount of wear experienced by the paint is a function of the interaction between the delineation variables discussed in chapter 3. The variables that affect paint in particular are discussed below.

As presented in chapter 3, roadway geometry and traffic characteristics will determine the number of wheels passing over a certain portion of the marking. Also, the traffic composition will determine the average loading cycle for each wheel pass. These factors are directly proportional to wear of the marking. In combination with the effects of the other delineation variables, they will usually correlate well with service life.

The type and condition of pavement surface is another variable that affects service life. Paint normally lasts longer on bituminous asphalt than on PCC. On the average, centerlines placed on PCC may require repainting each year, whereas similar markings placed on AC may require remarking every two years. It has also been found that paint laid over paint will perform better than on new installations, assuming that the base layer of paint is in fair condition and is on a stable substrate.

The climate will have a direct effect on service life of a painted marking. It is particularly important for paint, which often has a service life of less than a full weather cycle of four seasons. Paint wear is especially heavy in cold weather. In certain climates, painted markings applied in the fall will have a shorter service life than those applied in the spring.

Aside from the rate of wear, the marking's service life will be determined by the mode of failure and the paint's formulation and thickness. Different paint formulations affect service life, but the more durable paints tend to be proportionately more expensive.

Thicker paint films on stable pavement surfaces usually provide increased durability. However, this is not a linear relationship. The additional service life of a marking thicker than 15 mil (0.4 millimeters) is proportionally less than the increase in thickness.

Additional thickness of paint will lengthen service life only if the failure is caused by wear. Sometimes the failure mode is by loss of bond within the paint or at the paint-substrate interface. In this case, the additional thickness of paint normally does not extend service life.

Because of the variations in the parameters associated with service life of paint, each highway agency should develop its own estimated service life based on local conditions and experience. An "average" service life based on a compilation of nationwide experience has little meaning.

INSTALLATION, MAINTENANCE, AND REMOVAL

The equipment, procedures, and policies involved in the application of paint have a profound influence on the ultimate performance. This is equally true for all forms of delineation treatments. Among the major concerns are compatibility of materials and equipment, size and capabilities of crew, protection of crew, and traffic control during the application process.

While it might be assumed that the material chosen would dictate the type of equipment, in practice the opposite is usually true. That is, the material is often selected based on the capabilities of available equipment. This is one reason for the resistance in State highway agencies to the use of new materials.

For example, it may be determined that a rapid-drying, hot-applied paint will be economical, durable, and safely applied for a certain project. If the highway agency's equipment is compatible only to cold-applied paint, most highway agencies will use the cold-applied materials. Capital expenditures for new equipment or the use of a contractor are often beyond available budgets.

This illustrates that compromises must be made among all elements of the delineation treatment. Few decisions are

simple enough that they can be made independent of other concerns.

Application Equipment

Painted markings can be applied with a variety of equipment. Selection of the proper equipment will depend on the size of community, miles of roadway, geographic characteristics, pavement surfaces, and the types of markings.

Equipment falls into two broad categories. The first is the small, self-propelled, manually-controlled striper with very low material capacity. The other is the heavy-duty, multilane, truck-mounted striper.

The smaller striper is generally used for marking crosswalks and other transverse markings and legends. Commercially developed stripers may have several unique characteristics. One type may be self-contained with a small engine to propel and operate the air compressors, paint and bead tanks, spray gun, and bead dispenser. In other stripers, the compressor may be an auxiliary unit with a hose connecting it to the spray gun. Typical small-scale stripers are illustrated in figure 21.

The larger truck-mounted striper is almost always used for longitudinal markings. These stripers are available commercially or can be customized to a highway agency's specifications. While the specifics may differ, heavy-duty stripers typically have the following characteristics. The bed must be large enough to carry all the necessary marking equipment. The engine should have sufficient power to maintain a steady speed up grades. This is needed for the spray equipment to produce a uniform marking. The striper is equipped with special warning lights. Arrow panels should be mounted on the striper if it is not followed by a shadow vehicle. The front of the striper is usually equipped with a device, such as a small caster, that will enable the operator to follow a target on the

pavement or to follow a previous marking. The device must be retractable so that it can be lifted free of the pavement when the marking operation is discontinued or the device is not in use. A typical layout of a large-scale striper is shown in figure 22. Photographs of some current models of stripers are shown in figure 23.

Two different methods are used to supply the traffic paint to the spray guns. In the first, the paint drums are lifted from a supply truck to the striper by a hoist and the paint is pumped directly from the drums to the paint guns. A valve in the hose permits pumping from either of two drums. In the second method, paint tanks are located on the striper. These may be filled from drums or tankers by either mechanical pumps or air pressure. In both methods, screens must be used in the lines to help prevent contaminants in the paint. The screens must be freely accessible so they can be cleaned frequently. Additional screens should be located close to the paint spray guns. The hoses must be resistant to the cleaning solvent and to the solvent used in the paint.

The striper should be equipped with an accurate speedometer so that a consistent speed can be maintained. A volume meter for each paint supply is valuable for monitoring the quantity of paint applied.

An air pressure system transports the paint to the spray guns at a pressure determined by the quantity of paint to be delivered. It also supplies air at a lower pressure to a jet at the paint nozzle to atomize the paint. Air also moves the glass beads from the bead tank to the gravity-type bead dispensers. When hot paint is used, the glass beads are applied pneumatically. Air is also used in control valves for the paint guns. Some highway agencies use an air blast just ahead of the paint gun to blow loose paint chips and other debris from the area being painted.

The air supply comes from a compressor that is driven by a gasoline or diesel engine. This is mounted on a skid frame bolted to the bed. There should be instrumentation to ensure that the engine power matches the load on the compressor. Protective devices are desirable to shut down the engine in the event of a malfunction.

The air pressure is also connected to the cleaning system, which is a tank of paint solvent that can be connected to the paint lines and nozzles by supply valves. The lines, nozzles, and screens must be cleaned

only after use. The cleaning solvent is returned to a drum on the striper.

The paint spray guns and bead dispensers are mounted on carriages underneath the truck bed; they attach just behind the rear axle. This is illustrated in figure 24. The carriages can be moved laterally by the spray gun operator. A positive placement of the carriage is applied. If edgelineing is done at the same time as centerlineing, two carriages are needed.



Figure 21. Small paint application units

The paint spray guns and bead applicators are timed so that the bead applicator starts at the appropriate time after the paint spray gun starts. All spray guns and bead applicators are controlled by an intermittent timer. This device consists of a timing mechanism driven by a ground contact wheel. A typical control panel for these devices is shown in figure 25.

Heating the paint prior to application has proven effective at achieving more uniform consistency under changing temperature conditions and in reducing drying time. Low temperatures (up to about 120 degrees Fahrenheit/49 degrees Celsius)

can be obtained by using a heat exchanger in the paint supply tank. This uses hot water from the truck radiator or from the compressor radiator. Temperatures higher than this require that the paint supply lines be jacketed and hot water must be supplied to the jackets.

Temperatures above 180 degrees Fahrenheit (82 degrees Celsius) generally require an external heating system to supply heated liquid (a coolant or special fluid) to the heat exchanger and to heat the paint lines. Some stripers that are used for application of quick-drying heated paint have a compressor located behind the

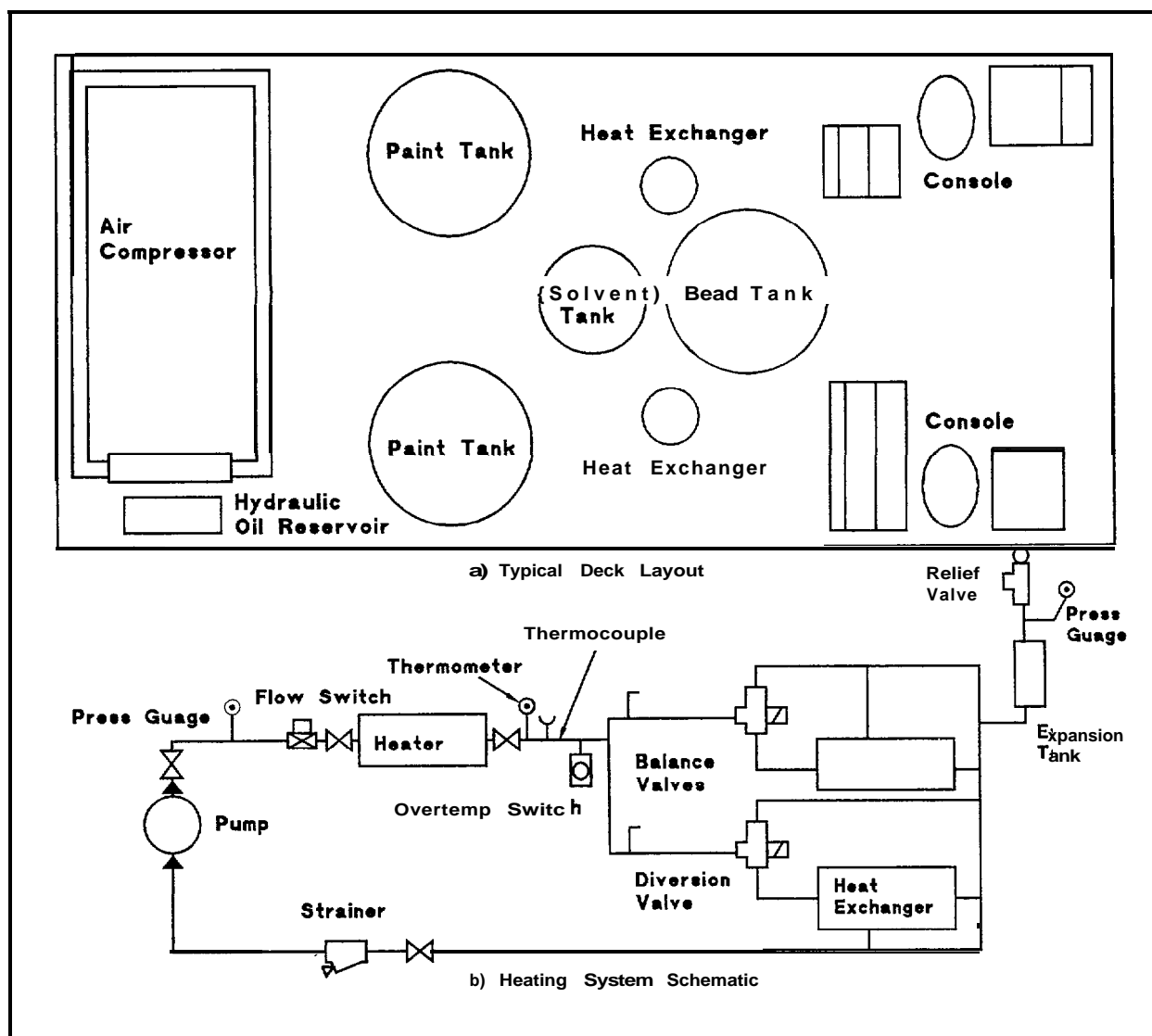


Figure 22. Layout of large-scale paint striper

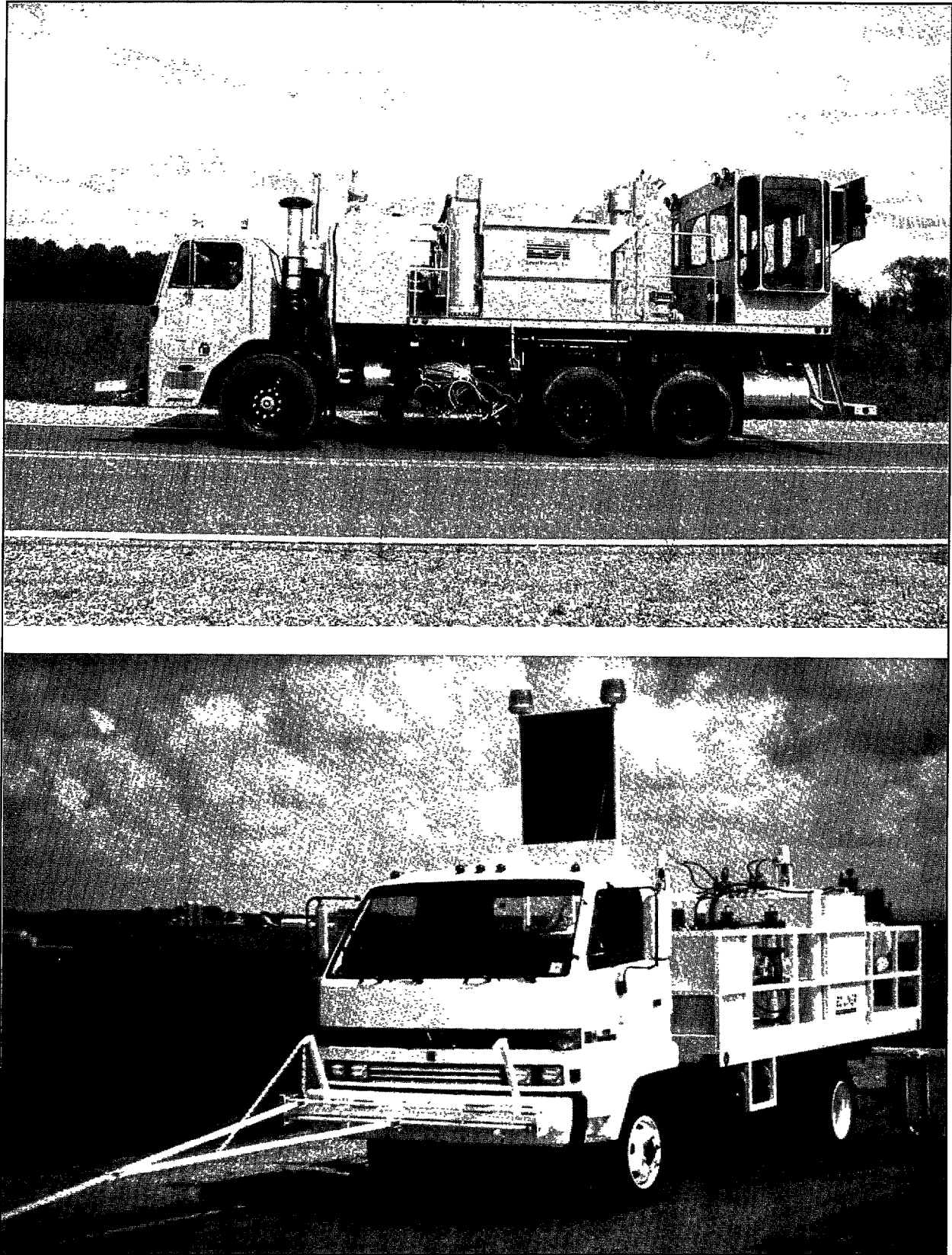


Figure 23. Truck-mounted paint application units

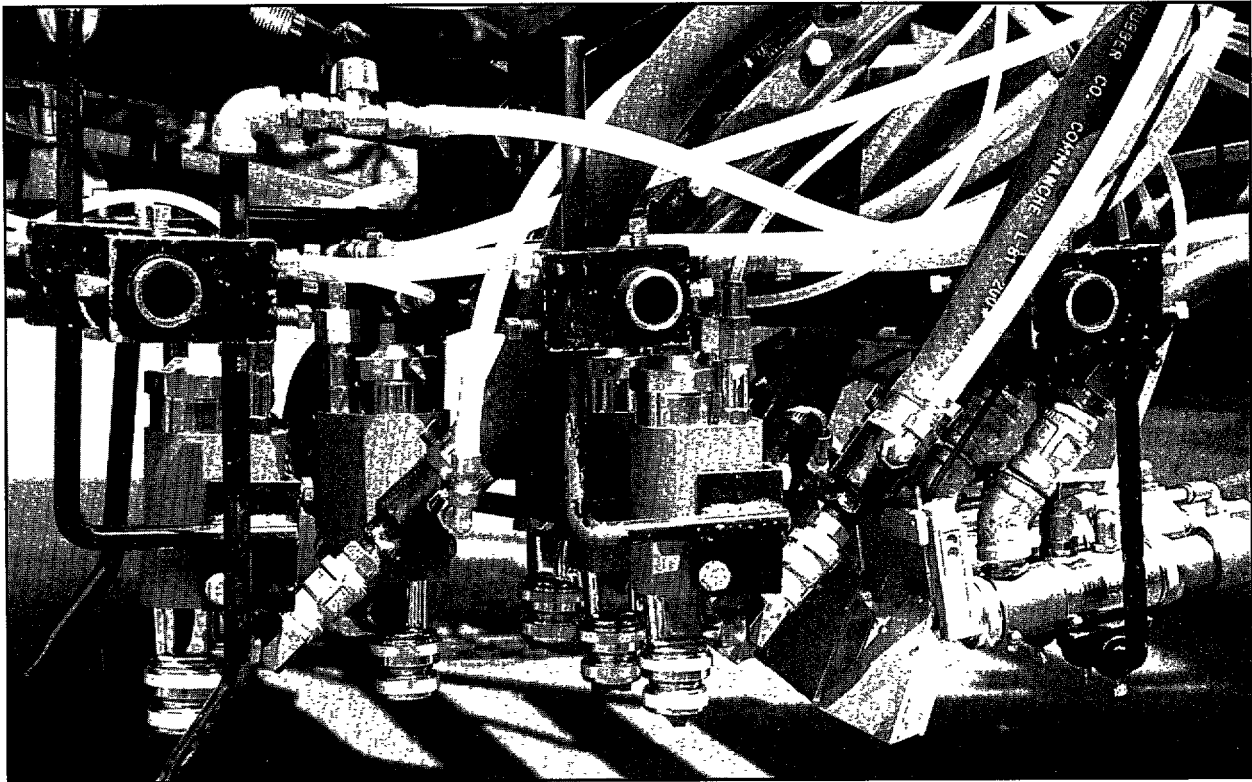


Figure 24. Paint and glass bead spray applicator

operator and a heat exchanger mounted on the bed.

One type of striper is capable of applying material at pressures up to 2,000 pounds per square inch (14,000 kilopascals) and temperatures up to 350 degrees Fahrenheit (177 degrees Celsius). A striper used by the Florida DOT has a million-Btu (293-kilowatt) heater, a 250-cubic feet per minute (0.12 cubic meters per second) compressor, dual steering, and a paint temperature capability of 225 degrees Fahrenheit (108 degrees Celsius) while painting three markings.

One type of California striper generates heat in a rotational mechanism that uses mechanical energy to heat paint. No heat exchanger is needed. Temperatures can be controlled to within 1 degree Fahrenheit (0.6 degrees Celsius) over a range of ambient to 400 degrees Fahrenheit (204 degrees Celsius). It has been used with various materials and at speeds up to 20

miles per hour (32 kilometers per hour). Paint drying time, depending on material,

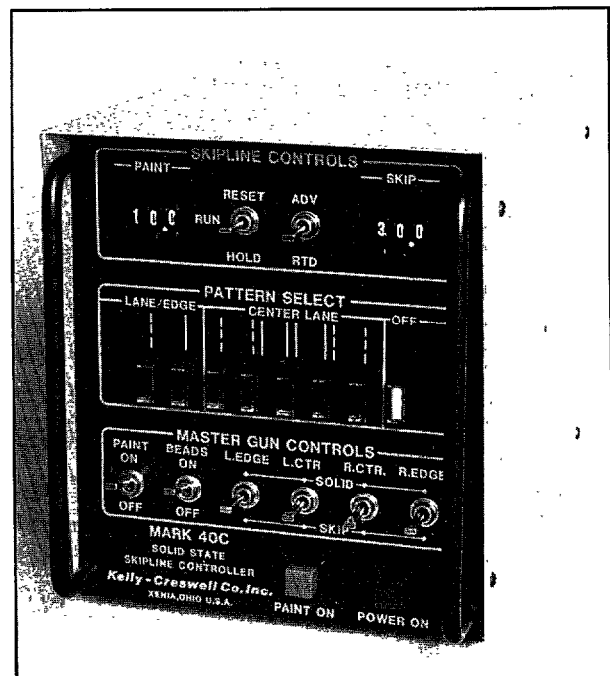


Figure 25. Paint control panel

ranges from 6 to 90 seconds. Operation is by a two-person crew plus a follow-up truck with warning sign. This striper can mark from the right or left side (retractable spray guns at the centerline of tandem axles) or straddling the marking (sulky in front of truck). Up to three markings can be applied simultaneously. Another feature of this striper is a multiple-nozzle airless spray gun capable of layer operation; e.g., two thin layers of paint, followed by beads, then another layer of paint and a top course of beads. Because it is not necessary to clear the paint lines and spray guns at the end of a day's work, a full day of marking is possible. This striper is reported to reduce bead use by 15 percent and paint by 10 percent over older designs.⁽⁴⁷⁾

Missouri, North Carolina, and several other States have stripers that use a high fluid pressure (1,400 to 1,800 pounds per square inch/9,600 to 12,400 kilopascals) spray system. Air atomization of the paint is not required. Wyoming has stripers with motors to drive the high-pressure pumps.

Crew Size for Installation

Although heated and quick-drying cold-applied paints do not require protection of the freshly painted marking from traffic, slower drying paint materials require some form of protection. The type of protection required dictates the size of the crew.

The most common form of protection is traffic cones. The striper may be equipped with an apparatus that sets the cones. Alternately, a platform at the rear or side of the striper can accommodate a crew member who sets the cones manually. In other operations, the cones are placed from a following truck equipped with an arrow board. An example of how these cones may be placed is shown in figure 26.

Some highway agencies pick up cones manually. In other States, machines for picking up cones have been developed. One such machine developed by ADDCO (St.

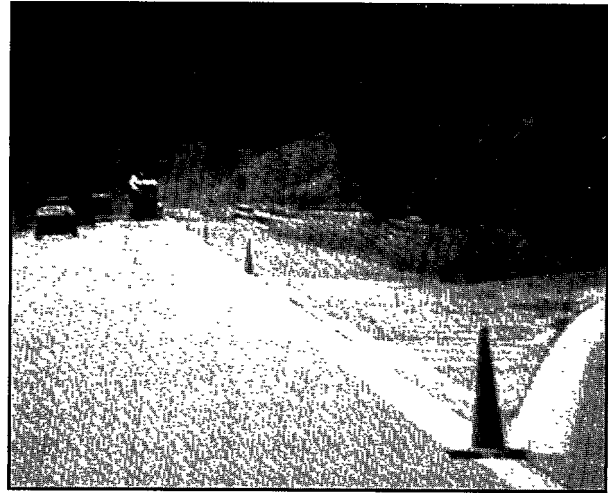


Figure 26. Coning for paint application

Paul, MN) and marketed commercially, consists of a large wheel that will pick up or set down cones, allowing the operator to remain in the bed of a standard pickup truck.

On heavily used roadways, some highway agencies will use one or more trucks with arrow boards following the striper. These following trucks direct traffic and protect the marking from traffic. Extreme care and caution in these situations are required to protect the work crew.

The size of the crew depends on the nature of the operation and on each highway agency's policy. If centerlines, edgelines, and no-passing lines are applied simultaneously, two spray gun operators are needed. Thus, considering that the striper has a driver and assistant, a crew of four is required. A supply truck and operator is required for most operations. If cones are needed, another worker is required. The crew coordinator usually follows the striper. The cones must be retrieved by another truck with two or three workers. If cones are not needed, supporting trucks are used for protection of the marking and generally follow at intervals of about 500 feet (150 meters).

The simplest marking operation requires about five workers and two trucks, in addition to the striper. Considerable planning and coordination are needed to attain an efficient and low-cost operation. Because the marking operation is seasonal in many States, the markings should be placed as early in the morning as possible, but not before conditions are suitable. Because of rigid work hours, marking is too often started in the morning before the pavement surface has dried.

As in many other fields, quality is often sacrificed because of the push for increased production. Shortcuts in application are seldom cost-effective. Materials can be wasted, machinery clogged, and the quality of the marking degraded if proper attention to detail is abandoned in favor of a few additional miles of marking.

Pretreatment of Pavement

Early experience with traffic paints suggested that better adhesion might result from pretreatment. It was fairly well-documented that repainted markings performed better than the initial application on bare pavement. It was hypothesized that pretreatment, particularly on PCC, would lengthen the service life of paint.

However, actual performance of pretreatments has been erratic; several methods have been used without significantly increasing durability. Applying a light coating of paint without beads as a sealer on new pavement surfaces has proved a successful practice used in some States.

The first (primer) coat, laid at 4 to 5 gallons per mile (9.4 to 11.8 liters per kilometer), dries rapidly and seals the pavement. This eliminates discoloration of asphalt from the solvent in traffic paint. It also improves adhesion on PCC.⁽⁴⁸⁾

Another problem is inadequate cleaning of pavement surfaces. Tests have shown that clean surfaces improve adhesion. A

field study was conducted to assess the various types of surface preparation techniques.⁽⁴⁸⁾ The techniques studied included grinding, airblasting, sandblasting, burning, washing (hydroblasting), acid etching, and wire brushing.

Of the different methods, wire brushing worked best with the application technique used. It was easy to use, worked well on irregular surfaces, did not damage the surface, had no logistics or time lapse problems, and effectively removed road film. In this method, a wire brush is mounted in front of the centerline spray gun and is controlled by the same circuit. The gun and brush thus activate and deactivate simultaneously.

Brushing pressure on the road is controlled by a regulator on the air supply. It appeared that optimum brushing occurred when the brush was at its highest speed (600 revolutions per minute) and a broom pressure that caused a 0.25-inch (0.17-millimeter) deflection of the side bristles. Too much pressure resulted in excessive fiber deflection, early failure, poor cleaning action, and unnecessary strain on the drive parts.

The cost for the wire brushing operation during this 1979 study totaled about \$0.26 per mile (\$0.16 per kilometer). It was concluded that the service life of paint was not noticeably improved by brushing under the conditions of the field tests (hot, dry weather, relatively clean roads). It may still be useful for other road conditions and is probably more important when applying spray or extruded thermoplastic markings, since they do not have the wetting capabilities of solvent-based paint.

Premarking of Roadway

It is generally necessary to premark the pavement surface before applying a new pavement marking. The customary method of premarking is to use a string or pieces of pavement marking tape and make spots

approximately every 5 feet (1.5 meters). When working in traffic, the workers applying premarkings must be protected with signing, flaggers, and lane closures. Another procedure is to premark the pavement with a dribble line using a small-scale striper. Using the striper ensures rapid placement of a guideline with a minimum number of control points (figure 27).

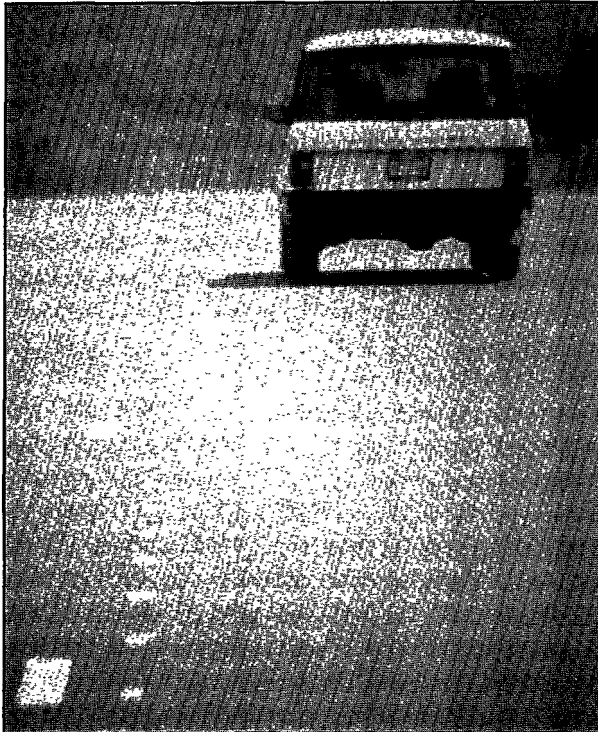


Figure 27. Premarking technique

For resurfacing jobs, a temporary offset marking is painted on the shoulder before the overlay is placed. The striper then paints the marking on the new surface using the offset marking as a guide. This method has proven itself in the past.

If a pavement marking has been obliterated by resurfacing, FHWA policy requires that markings be in place before the roadway is opened to traffic. In some States, heavy dribble lines are placed to serve traffic until the surface is cured and the standard markings can be painted. If used, dribble lines should not be more than 3 inches (7.6 millimeters) wide, so that they

can be completely covered when the standard marking is applied. Use of dribble lines is discouraged by the FHWA, however.

Scheduling of Marking Activities

Proper maintenance requires repainting of markings when the contrast, base film, or retroreflectivity is lost. The decision to repaint and schedule the activity are duties of the highway agency's maintenance chief. The highway agency usually has an established policy to help in this process. The availability of materials, equipment, and crews is also important. Materials must be selected, purchased, and stored. Equipment must be serviced and maintained to ensure proper operations and prevent breakdowns while on the road. Trained crews must be available and appropriately scheduled.

Some highway agencies have predetermined schedules that identify sections of roadway to be marked periodically. A computerized marking program should be used for a large volume of roadways to assure a cost-effective allocation of equipment, crew, and materials. When less mileage is involved, a manual scheduling process is commonly used. In either case, past experience and the highway agency's policy define the number of times a roadway must be marked per year.

Other highway agencies may prefer to schedule remarking based on night inspection of the various facilities. In some cases, residential streets and other low ADT roadways are simply marked on a periodic basis. The busier, higher ADT roads are scheduled on an as-needed basis using night appearance to judge overall performance.

Determining when to replace painted markings is, at best, an inexact science vulnerable to subjective judgement and budgetary pressures. Several highway agencies have reported that overtime cost for night inspection cannot be justified,

especially since the resulting evaluation is based on a subjective opinion.

Whatever the method used, maintenance personnel should have knowledge of local traffic and climatic conditions and must be experienced with a variety of delineation materials. These two criteria are considered equally important for scheduling remarking activities.

The weather patterns of the area determine, to a large extent, the time period available for maintenance. In high snowfall areas, for example, painting is usually limited to the late spring, summer, and early fall months. The treatments and techniques used reflect the short service life of painted markings under heavy winter conditions.

Repainting activities should be scheduled in coordination with major improvement programs and with other maintenance activities. Resurfacing, realignment, or changes in traffic patterns that would require new or repainted markings may render previously scheduled repainting unnecessary. If marking activities are not coordinated with other maintenance, new markings may have to be removed. This is an expensive mistake. Unfortunately, this type of oversight is a common occurrence.

This is not to suggest that repainting should be indefinitely postponed because of planned changes or improvements, particularly if the markings are significantly degraded in a hazardous location. Other options are available, such as varying the type of paint, reducing the marking's thickness, or using temporary markings. These options should be carefully considered when changes are anticipated. If a highway agency is planning to postpone remarking, it should be aware of the potential safety hazard and legal implications from the lack of adequate delineation.

Warehousing and Storing of Materials

Traffic paint is usually furnished in accordance with a highway agency's specifications. It is tested at the factory, placed in sealed containers, and shipped ready to be used. The size of containers is specified by the highway agency and will usually be 5-gallon (19-liter), 30-gallon (114-liter), or 55-gallon (208-liter) drums.

Specifications for traffic paint are written to ensure against caking and excessive settling of the pigment. However, it may be necessary to stir the paint to ensure complete remixing prior to use. Paint that has settled and formed a hard cake at the bottom of the container should not be used. Instead, full data regarding lot number, quantity, and other pertinent information should be reported and arrangements made for such paint to be returned to the manufacturer.

Traffic paint that will remain in storage for some time should be stored upside down so that any deposit or settling will occur on the lid of the container. When it is opened, the settled pigment may easily be scraped off the cover and incorporated with the balance of the mix.

Occasionally a container of traffic paint will show a green film on the top and along the edges of the container. This discoloration, which disappears immediately upon mixing, is of no significance in the performance of the paint. However, sometimes traffic paint will contain "skins." Specifications usually require the lining of traffic paint containers to be resistant to the solvent and prevent skins from forming. A skin might form as a result of a manufacturer using the wrong materials for liners in paint containers. This lining will loosen and form skins. Paint containing skins of this character should not be used, and arrangements made to return it to the vendor.

Paint should be mixed thoroughly before being placed in the paint tank of the application equipment. Thinner should not be necessary. (The wash thinner usually furnished is intended solely for cleaning equipment and not for thinning the paint).

A 1979 study of the cost-effectiveness of various storage and warehousing practices specifically addressed the economic feasibility of recycling drums for shipment and storage of paint, the use of 55-gallon (208-liter) drums versus 30-gallon (114-liter) drums, and bulk paint storage versus drum storage.⁽⁴³⁾

Several States tried using recycled drums, but the drums had a significant leakage problem because the lids did not fit properly. It was concluded that this did not represent an economically feasible alternative, considering the loss of paint through leakage and the relatively small cost saving realized by using recycled drums.

The study showed that the use of 55-gallon (208-liter) drums in lieu of 30-gallon (114-liter) drums resulted in a 40 percent reduction in the number of drums. Based on a comparison of drum costs and their resale values for both sizes, it was determined that considerable savings in purchasing costs alone could be realized.

In addition to the obvious savings of about \$0.35 per gallon (\$0.09 per liter) afforded by eliminating the cost of the drums, it was estimated that about 3 gallons (11.4 liters) of paint remain in each discarded barrel. Thus, there would be an additional saving due to reduction in waste. The installation, maintenance, and energy costs of storage facilities will offset some of these potential savings.

The main problem in converting to the larger drums lies in handling these drums at the various storage areas. The full 30-gallon (114-liter) drums can be loaded by hand into supply trucks. To handle the 55-

gallon (208-liter) drums, forklifts or other equipment are needed. Additional cost for equipment may therefore offset some of the initial savings.

A real potential for saving appears to exist in the bulk paint storage concept. Possible cost saving, as well as the ability to store large quantities of paint in a small area, make the bulk storage method an attractive alternative.

Removal of Painted Markings

Every highway agency needs to provide a capability for removing existing markings that no longer define the safe path of travel. The difficulties involved in the removal of markings have been compounded by the increasingly successful effort to improve paint durability and adhesion.

Traditional Methods

A 1986 study by the New York State DOT investigated the traditional methods of pavement marking removal.⁽⁴⁹⁾ Those methods are discussed below.

Chemical. Chemical paint remover can be applied to the unwanted pavement marking by hand or machine. It is allowed to react for 10 to 20 minutes, depending on pavement temperature. A water jet-500 to 2,500 pounds per square inch (3,400 to 17,000 kilopascals)-then flushes the chemical and paint from the pavement. This method was claimed effective on both AC and PCC pavements, but damage may result if the chemical is left on the pavement too long or if water jet pressure is too high. This procedure is limited to temperatures above freezing and is most effective for markings 10 to 20 mil (0.26 to 0.53 millimeters) thick. Thick paint buildups require a second or third application, thus slowing the operation and increasing cost.

Grinding. This method was reported to remove markings effectively from both

concrete and asphalt pavements. Because pavement marking thickness does not affect the extent of removal, grinding may also be effective on thermoplastic. However, pavement damage is a problem because grinding alters pavement surface texture and appearance and may even gouge the surface, thus creating a scar in place of the obliterated marking. Grinding was reported to be slow and expensive, and not recommended for open-graded asphalt or rough-textured pavements.

High-Pressure Water Jet. A high-pressure water jet-2000 to 3000 pounds per square inch (13,700 to 20,500 kilopascals)-was reportedly effective in removing pavement markings from PCC. It was claimed to remove about 90 percent of the marking from AC, but an outline of the obliterated painted marking may remain. This method, which is restricted to temperatures above freezing, may also remove some fine aggregate from asphalt pavement.

Hot Compressed-Air Burning. This method uses a high-temperature blast (more than 2400 degrees Fahrenheit/1315 degrees Celsius) of exhaust gases from propane combustion in a high-velocity compressed-air stream to oxidize the marking. Good results were reported in removing the marking, but the air blast also removed some pavement material. The obliterated paint and beads remain bonded to the pavement surface, creating a scar. A wire brush removes some of this smudge, but the scar is still visible during the day as well as at night. Weathering and traffic wear tend to make this pavement discoloration less obvious, but it may still be visible after three months. As in any burning method, asphalt pavement and preformed expansion joint material in concrete pavement may be damaged if the burner head moves too slowly.

Excess-Oxygen Burning. In this system, two wide, flat burner heads are mounted in tandem on a simple hand-propelled cart.

The first burner creates a high-temperature flame (4,500 to 5,000 degrees Fahrenheit,/ 3,800 to 2,760 degrees Celsius) of propane and oxygen directed at the pavement surface. A second burner tip directs pure oxygen at the burning surface to accelerate oxidation of the marking. Best results are achieved on paint layers that are thin, and markings more than 20 mil (0.53 millimeter) usually require more than one pass. Obliterated paint and beads remain bonded to the pavement surface, but can be removed using a wire brush. After a few weeks of weathering and traffic wear, this scar normally blends into the surrounding pavement and is no longer visible. The rate of removal varies with the thickness of the marking. Up to 20 mil (.53 millimeters) of a typical alkyd-chlorinated rubber paint marking can be removed each pass at a rate of 7 to 15 feet (2 to 5 meters) per minute. For thicker paint, more than one pass may be necessary. As the ash residue accumulates, it shields the marking from further penetration of the flame.

Hydroblasting. This method uses a high-pressure water blast in combination with sand to sandblast pavement markings hydraulically. Blasting is performed at pressures of 5,000 to 10,000 pounds per square inch (34,250 to 68,500 kilopascals), and sand is used at a rate of 300 pounds per hour (136 kilograms per hour). Hydroblasting reportedly removes all paint and beads from PCC with no apparent damage. A thin, white-gray slurry remains on the pavement, but after a few weeks of weathering and traffic wear, the scar is no longer evident. This method is less effective on AC than on PCC, and in some cases surface aggregate may be scoured or polished, resulting in a scar that can be visible at night and during conditions of low visibility. Weathering and traffic abrasion eventually remove this scar. Hydroblasting, which requires a long equipment train and is confined to temperatures above freezing, is slow. However, some promise has been reported for removing painted markings from asphalt pavement.

Sandblasting. One of the more widely used methods for marking removal, sandblasting achieves fair to excellent results on both AC and PCC. However, operator skill is necessary for effective removal of markings without pavement damage. Sandblasting is not effective on open-graded asphalt pavement because it is difficult to remove markings completely without damaging the pavement surface. It is generally slow, requiring a large equipment train, and leaves residue that must be cleaned up.

Table 3 compares the effectiveness of the various methods in removing different types of marking materials.

Painting over incorrect markings with black paint or bituminous solutions is specifically prohibited by the *MUTCD*. Such treatment has proved unsuitable because the original marking eventually reappears as the overlaying material wears away under traffic. In addition, markings that were covered in this way are still visible under certain conditions (low angles of illumination) due to preferential reflection from the two contrasting surfaces—the painted marking and the adjacent road.

The best method for marking removal is a treatment that affects the roadway surface

as little as possible. It should not materially damage the pavement surface or texture. Because chemical treatment may cause damage to the pavement surface or drainage channels, it is seldom completely satisfactory. Removal of markings by grinding is not considered completely successful as some remnants of the marking usually remain. Sandblasting has been the preferred method of treatment.

Sandblasting is effective particularly when the pavement is rough and porous. The process does little damage to asphalt and the resulting scarring is barely noticeable. Sand deposited on the pavement should be removed to prevent drainage problems or a traffic hazard.

New Techniques

A new method similar to excess oxygen burning was developed by an independent contractor a few years ago. It consists of a specially designed burner to combust propane and oxygen in a wide flame composed of a large number of separate tips.⁽⁵⁰⁾ After combustion, the marking is treated with a mild scarifier. The field tests indicated that use of the cooler flame results in scarification and more damage to the pavement than excess oxygen burning. Field experience has been limited.

Table 3. Effectiveness of removal methods

Removal method	Paint	Thermoplastic	Epoxy	Plastic Tape	Foil Tape
Sandblasting	Good	Slow	Good	Ineffective	Very slow
High-Pressure Water	Good	Slow	Good	Ineffective	Ineffective
Hydroblasting	Good	Slow	Good	Ineffective	Ineffective
Grinding	Good*	Good*	Good*	Ineffective	Ineffective
Excess-Oxygen Burning	Thin only	Ineffective	Ineffective	Ineffective	Good
Chemicals	Slow	Ineffective	Ineffective	Ineffective	Ineffective
Hand Removal	NA	Very slow	NA	Very slow	Ineffective

* - Heavy scarring to pavement

NA - Not applicable to this material

Another independent contractor developed a new mechanical removal technique.⁽⁵¹⁾ This method applies hardened steel cutter wheels to the marking to weaken the paint-pavement bond. Application of high-pressure water jets completes the paint removal. This method showed significant promise in small-scale tests but has not been used in large-scale application.

INSPECTION

Inspection of painted markings is vital for cost-effective applications. Inspectors must be on the job site to ensure that the contractor is correctly applying the markings. Use of performance specifications has reduced the importance of inspection. However, there are legal problems with trying enforcement of performance specifications. The main points for inspection of painted markings is discussed in this section.

Preapplication Inspections

Before application, the inspector must check the following:

- Materials used must be from a prequalified vendor or must be specifically approved by the State's material laboratory.
- The pavement being marked must be in appropriate condition for the material being applied. Some materials, such as two-component epoxy paints, have different requirements. They may be applied on damp pavements at low temperatures. However, they may not be applied over other pavement marking materials. The material being applied will dictate the pavement condition requirements. It is most important that the pavement be clean and dry. If marking is begun early in the morning, moisture tests should be performed. Marking should be postponed until these tests are successfully completed.
- Premarkings should be adequate to guide the marking truck operator in applying well-aligned markings. They should be less than 3 inches (7.6 millimeters) wide to ensure complete coverage by the pavement marking application.
- Air and pavement temperatures must match the requirements of the material being applied. Again, different materials will have different requirements. Check actual conditions against the manufacturer's recommendations. Table 3 gives typical ranges of temperatures allowed for various materials. If any temperatures are outside the recommended values, marking should be postponed.

Application Inspections

Inspectors must check the following during application:

- Exposure to traffic should be minimized. Coning or other measures must provide good protection for both workers and the new pavement marking.
- New markings must be protected for all of their no-track times. No-track times for the different classes of materials are listed in table 3. These values will vary slightly based on specific material formulation.
- Tests should be made of application rate of glass beads by putting bags over the bead dispenser and driving a predetermined distance at normal marking speeds. The beads can then be weighed and application rate calculated.
- Material application temperatures should be within the manufacturer's recommended ranges.
- Inspection of handling procedures and safety measures is vital for liability reasons. Many paints, such as polyester,

involve handling of potentially hazardous solvents or other materials.

Postapplication Inspections

After the marking has been applied, the following should be checked to test the application technique:

- Color should be checked with a standard highway color chip or a Tristimulus colorimeter (figure 28). Colors must conform to FHWA requirements for standard highway colors.

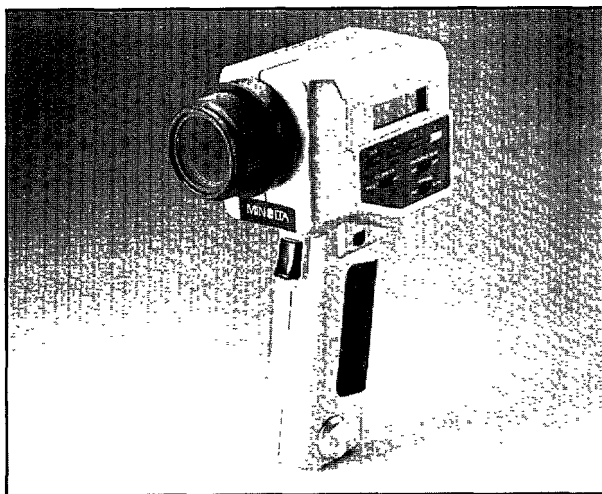


Figure 28. Portable Tristimulus colorimeter

- Thickness can be checked by placing duct tape in the marking truck's path, removing the duct tape and measuring thickness with a micrometer. The contract will probably specify the thickness to be applied and allowable tolerances. Typical thicknesses for paint systems are shown in table 4.
- The marking can be checked for adequate retroreflectivity using the sunlight/shadow technique or a portable retroreflectometer; the embedment and distribution of glass beads can be checked using a pocket microscope.

For detailed material on inspection, see chapter 11.

ENVIRONMENTAL CONCERNS

The use of volatile organic compounds (VOCs) in oil-based paint formulations is the subject of increasing concern to environmentalists. In fact, according to the California Air Resources Board, petroleum-based solvents used in paint and for cleanup purposes are the third largest source of air pollution in Los Angeles, San Diego, San Francisco, and Sacramento.⁽⁵²⁾

Because of the VOCs released in marking operations, they can be subject to certain environmental regulations. In fact, certain governmental agencies have begun to develop regulations specifically to regulate VOC release from marking activities. Some of these agencies and the regulations they have developed are discussed here.

State and Local Regulation

Following the lead of the Environmental Protection Agency and the latest research, the States have begun their own programs for instituting regulation of the environmental hazards created by marking activities. States that have done the majority of the work to date have been those with a serious pollution problem, such as California (Los Angeles) and New York (New York City). These regions have a particularly high population density and, therefore, correspondingly high pollution. The release of VOCs and other hazards from pavement marking operations only worsens the problem. These States have, therefore, begun to exercise control over these activities.

The need to reduce pollution resulting from the use of solvents, such as toluene, led to the development of a Model Rule in California for the control of hydrocarbon emissions. Approved by the California Air Resources Board in July 1977, the Rule prohibits selling or applying any coating containing more than 250 grams of VOCs per liter of coating (1.92 pounds per gallon).

This ruling became effective September 2, 1982.⁽⁵³⁾ In most cases, exemptions were granted that extended this date to September 1984.

In 1982, The South Coast Air Quality Management District (Los Angeles basin) enforced Rule 442, which limits VOC emissions to 600 pounds (272 kilograms) per day. This limits the application of solvent-based paint to 175 gallons (662 liters) per day for each marking truck.

The trend to restrict the volume of VOCs in commonly used solvents indicates that paint formulations are changing dramatically. Commercial paint manufacturers, as well as State materials laboratories, are seeking to reduce organic gas emissions. They are shifting from the conventional formulations to those using nonvolatile solvents. They are also using materials with solvent ratios, such as water-based or epoxy coatings.

Hazardous Materials

Before the development of the 1984 Model Rule by the State of California, Los Angeles had introduced Rule 66, which specified the type of solvent that could be

used in white and yellow traffic paint for air pollution control districts. Type I solvents, based on toluene and aliphatic thinner, can be used in all areas of the State, except in counties that comprise air pollution control districts. For counties located in air pollution control districts, Type II solvents consisting of methyl ethyl ketone, ethyl amyl ketone, and special aliphatic thinners have been specified.

Lead-Based Pigments

In addition to the hazard created by the solvents used in traffic paint, there is another environmental problem from the lead-based yellow pigment that has traditionally been used. The State of California recognized this problem also and initiated a research program to investigate lead-free yellow pigments.⁽⁵³⁾

The research found that it was simple to match the yellow color required for traffic paints with a lead-free pigment. However, in an exposure test with a lead-based pigment as a control, only the lead chromate pigment retained a positive yellow color after an appreciable exposure time.

Table 4. Application characteristics for inspection

Marking Material	Recommended Temperatures			No-Track Time* (Minutes)	Typical Thickness (Mil)
	Pavement	(°F) Air	Material		
Alkyd or Modified Alkyd Traffic Paint	>50	>50	120	7 or more	15
Chlorinated-Rubber Paint	55-85	55-85	110-130	3-6	15

Note: These are typical values only, for standard applications. Actual experience varies greatly depending on material type and formulation.

CHAPTER 5. THERMOPLASTIC MATERIALS

INTRODUCTION

The search for highly durable markings as an alternative to conventional traffic paint has been under way for more than 20 years. The growing popularity of thermoplastic has been attributed to its readiness for immediate use, superior durability, and potential for long-term economy and traffic safety. While the initial cost of thermoplastic can be as much as 15 times the cost of conventional painted markings, its long service life and improved visibility make it an attractive alternative in many situations. This chapter summarizes the current uses and suggested procedures for installation of hot-applied thermoplastic materials.

Hot-applied thermoplastic materials have been in use for many years and are considered a cost-effective alternative to conventional paint markings when durability is a prime concern. Because of the wide operational experience, the emphasis in this chapter is on the traditional applications of thermoplastic.

USES

Thermoplastic materials have the same basic uses as traffic paint (chapter 4). The application guidelines provided in the *Manual for Uniform Traffic Control Devices (MUTCD)* concerning standard colors, widths, patterns, and placement of painted markings also apply to thermoplastic.⁽¹⁾

Experience has shown that various thermoplastic materials serve some uses better than others. The most cost-effective and safest use is a function of the site-

dependent variables. Hydrocarbon-based thermoplastic should not be used as transverse markings because oil drippings tend to dissolve them. This limits their use for crosswalk or stop bar applications. The decision to use thermoplastic must weigh the site and material characteristics against the increased cost.

Because of the long service life and inherent difficulties in removing permanent thermoplastic markings, exercise care in their application. Changes in marking patterns should be kept to a minimum. Maintenance programs, permit work, and utility repair programs are examples of projects that may disrupt the marking schedule. All these possibilities should be considered for the roadway that is to be marked. This will help avoid installation of thermoplastic on a roadway that will be resurfaced soon after marking.

There are several clear-cut advantages of thermoplastic markings when compared with paint. Perhaps the most apparent advantage lies in the replacement factor. A single application of thermoplastic might replace 20 or more applications of paint (dependent upon site-specific variables and application characteristics). Thus, even though thermoplastic materials may cost 15 times as much as paint, they can be cost-effective when used properly. In addition, there is an advantage to having constant delineation on the road, as opposed to a short-lived paint. With a nondurable material, a significant fraction of the marking cycle takes place when a marking is no longer adequate and the roadway is simply waiting to be marked.

Various agencies have reported that thermoplastic markings typically last 3 to 15 times longer than paint. This number depends on the paint replacement policy and the specifications for the thermoplastic installation. The break-even point ranges from three to six years. That is, to be cost-effective, the thermoplastic markings must remain in place, with satisfactory retro-reflectivity, for a minimum of three to six years. By carefully selecting material and application technique for a given installation, a balance can be achieved between service life and the higher initial cost.

While thermoplastic installations are frequently practical in terms of durability and visibility, users agree that it should not be assumed that such installations are appropriate for all situations. The following observations represent a summary of experience to date as reported by user agencies.

- Thermoplastic should not be applied on new Portland cement concrete (PCC) facilities. A one-year curing period is recommended prior to installing thermoplastic. Even after this one-year period, a primer-sealer should always be used when applying thermoplastic to PCC.
- Alkyd-based thermoplastic markings perform exceedingly well as transverse markings. Hydrocarbon-based transverse markings, however, tend to deteriorate rapidly because of motor oil drippings.
- Thermoplastic materials are rated as the best marking material by more highway agencies (36.5 percent) than any other. However, highway agencies generally consider it to be one of the more sensitive materials to apply.⁽⁵⁴⁾

MATERIALS

Hot-applied thermoplastic materials are synthetic resins that soften when heated and harden when cooled without changing the inherent properties of the material. The formulation of thermoplastic pavement markings includes three basic components: plastic and plasticizer (binder); pigment and fillers; and glass beads. The exact chemical composition varies considerably. Formulas of commercially available materials are proprietary and continually change as the price of chemical components fluctuates. For this reason, composition is usually specified in terms of minimum percentage by weight of each basic component. A list of specification sources is given in appendix C.

Although the percentage by weight of the components varies among specifications, a typical range is as follows:

Binder	15 to 35%
Glass beads	14 to 33%
Titanium dioxide (TiO ₂)	8 to 12%
Calcium carbonate (or other inert filler)	48 to 50%

Types

Thermoplastic materials are classified by the type of binder used. Two materials receive the majority of use in current applications. Alkyd-based thermoplastic markings have probably the largest variety of uses. They use synthetic alkyd resins for a binder. For this reason, they do not deteriorate from motor oil drippings in the way that hydrocarbon-based thermoplastic does. Hydrocarbon-based thermoplastic markings are generally used for longitudinal marking applications because of their susceptibility to oil droplets. They use petroleum-based organic compounds as a binder.

Properties of Thermoplastics

Thermoplastic materials are, by definition, materials that can be heated to a liquid state, reshaped, and cooled to form a new object. For thermoplastic materials, this cycle can be repeated any number of times without significantly influencing material properties.

In early uses, thermoplastic was heated to above 375 degrees Fahrenheit (191 degrees Celsius) and extruded onto the pavement at approximately 90- to 125-mil (2.2- to 3.2-millimeter) thickness. Retroreflective glass beads were premixed in the base material and a top dressing of beads was applied as the molten plastic was extruded. The material solidified, ready for use, within minutes. This marking was at least six times the thickness of conventional traffic paint. In addition to the inherent durability of the plastic itself, these markings provided a limited level of wet night visibility. The thick markings extended above the surface water film, negating some of the focusing effects of the film. This water film forms on wet roads, causing markings to lose their retroreflective properties. The physical mechanisms by which this phenomenon occurs, and how it affects retroreflectivity, are discussed more thoroughly in chapter 2.

Early hot-extruded installations had problems. Performance was erratic on PCC. Poor bonding and the formation of blisters within the marking were problems in high snowfall areas. Because of the poor bond, snowplow blades severely damaged the markings, especially on PCC.⁽⁵⁵⁾ Many of these problems were due to a lack of standard installation procedures. Pavement pretreatments were widely varied. Often the pavement was left uncleaned except for surface sweeping. Where primer coatings were used, their formulations also varied considerably. Given these circumstances, the performance of the early thermoplastic was unpredictable. Even when the major

factors were held constant, unexplainable variations in performance remained.

One of the main contributors to erratic performance of thermoplastic is the lack of quality control over temperature variables during the application process. Because of their flexibility, temperatures are probably the single most important concern when dealing with thermoplastic. Thermoplastic is designed to be easily melted and reformed. To accomplish this successfully, the required temperatures must be closely monitored. In addition, the material formulation must be exact to ensure that the material responds correctly to the predetermined temperatures.

Temperatures that are too high during the melting process can scorch the material. Inadequate temperatures may not melt the material fully, resulting in inadequate bonding. In addition, thicknesses must be monitored to ensure a good bond. If an application is not thick enough, the material on the pavement will not retain heat long enough for the thermoplastic to penetrate the substrate and become well-bonded.⁽⁵⁵⁾ Pavement and air temperatures that are too high or low will obviously affect heat transfer characteristics and thus adversely affect bonding.

Thermoplastic can be the most successful of all marking materials when properly applied. However, the material properties (melting temperature, formability, heat retention characteristics, and so on) that make them so useful also make them possibly the most sensitive material to apply. Control of application variables must be meticulous to achieve excellent marking performance.

Despite its problems, hot-applied thermoplastic shows much promise for improvement. Research continues into improved material formulations and application techniques. As a result, thermoplastic markings have changed and evolved. In addition to improvements in the

base thermoplastic materials and primer, modern equipment has made control of application variables much more precise. Hot-spray application may solve some of the problems with the process. Also, with more operational experience, performance and cost-effectiveness can be predicted more accurately.

PERFORMANCE

Thermoplastic markings, when properly applied, perform excellently. They are probably the most durable delineation technique, and their thickness also gives them some capability of providing delineation at night on wet roads. This section will discuss methods of measuring the performance of thermoplastic markings.

Service Life

Under some situations, hot-extruded thermoplastic pavement markings may be severely damaged by snowplow operations. Early research related the intensity of snowplow activity, as measured by mean annual snowfall, to thermoplastic durability.⁽⁵⁵⁾ This relationship is shown in figure 29. No correlation was found between other variables, such as traffic density, pavement pretreatment, primer type, and pavement age in this 1969 survey.

The variety of opinions, procedures, and experiences implies that the service life of thermoplastic markings depends on the installation site. Also, research project results should be tempered by the judgment and experience of personnel at each highway agency.

Although thermoplastic markings have been in use for a number of years, there is little agreement on their service life. Their excellent durability is established. However, establishing an expected service life for a particular material on a particular roadway is difficult. There are too many factors influencing performance to permit an average service life to be predicted with any

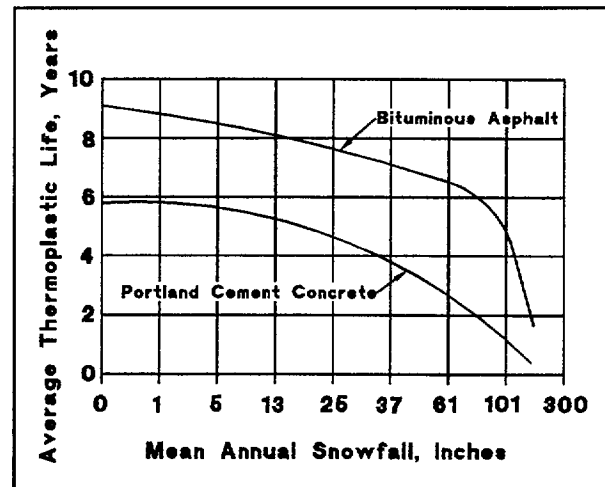


Figure 29. Average thermoplastic life vs. annual snowfall

confidence. Figures 30 and 31 express average service life as a function of volume and the durability of material as a function of traffic flow, respectively. These figures are representative of two of the more common methods used to predict service life.

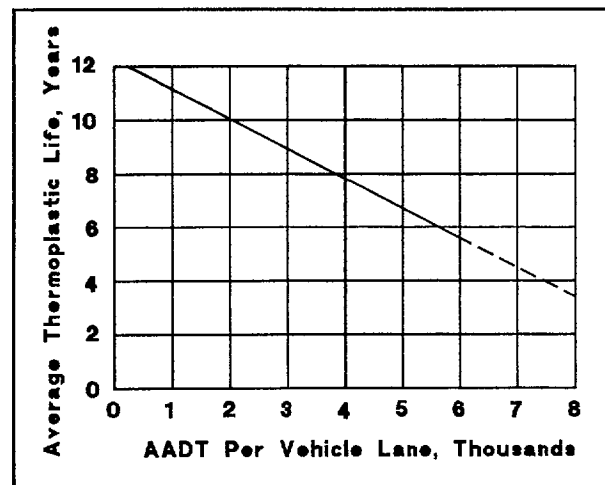


Figure 30. Life of thermoplastic markings as a function of volume

The remaining thickness or the percentage of retained area are the most common measures of service life. For example, the marking is assumed to be ineffective when the thickness falls below 10 to 15 mil (0.25 to 0.38 millimeters). The longitudinal loss of area is used more often

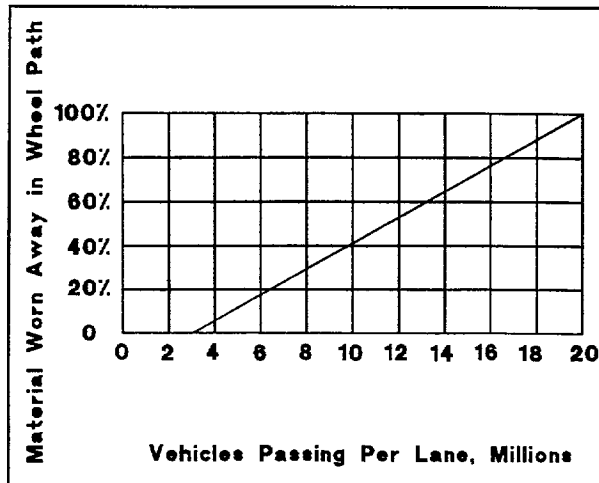


Figure 31. Performance of thermoplastic markings as a function of traffic flow

in determining service life, as well as loss of retroreflectivity.

Determining Service Life

Laboratory tests suggest that where an adequate bond is established, the action of the snowplow is only a minor contributor to thermoplastic marking loss.⁽⁵⁷⁾ The failure is probably caused by the freeze-thaw cycle characteristic of many snowfall areas. In any case, winter failures are more frequent on PCC than on AC because thermoplastic bonds better to asphalt surfaces. Thermoplastic is considered impervious to deicing chemicals and sands.

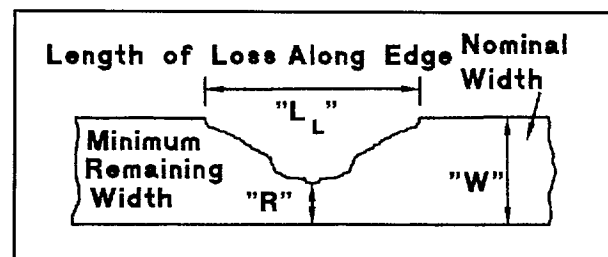
One survey of State highway agencies in a 1969 study reported a wide variation in thermoplastic performance and in agency expectations.⁽⁵⁵⁾ A suggested percentage of retention for contract warranty is given in table 5. This requirement is based on a hot-extruded application with 90- to 125-mil (2.3- to 3.2-millimeter) thickness.

The Texas Transportation Institute developed the following technique for determining percentage of thermoplastic retained.⁽⁵⁷⁾ The percentage retained is defined as the nominal area of the marking, minus the area of loss, divided by the nominal area, multiplied by 100.

Table 5. Warranty requirements for thermoplastic

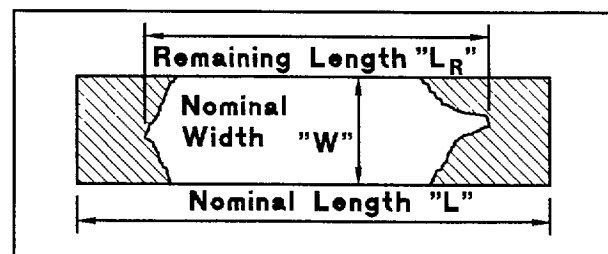
Duration After Acceptance	Minimum Retention	
	Longitudinal Lines	Transverse Lines
12 Months	90%	90%
24 Months	80%	75%
36 Months	60%	50%

Edge loss is loss from one edge that does not continue entirely across the marking. The area of loss is one half of the nominal width, minus the minimum remaining width in the loss area, times the length of loss along the edge.



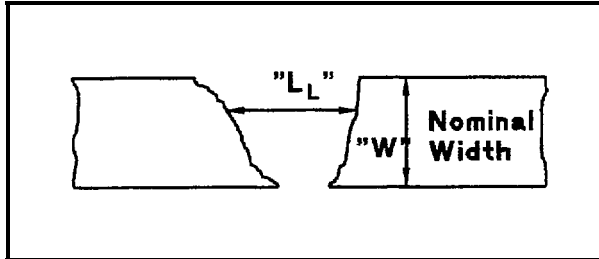
$$\text{Edge Loss} = L_1 = \frac{1}{2}(W - R) L_L$$

End loss is defined as the loss of thermoplastic at the end of the marking. The area of loss is the product of the remaining length measured along the centerline multiplied by the nominal width of the marking and divided by the nominal area.



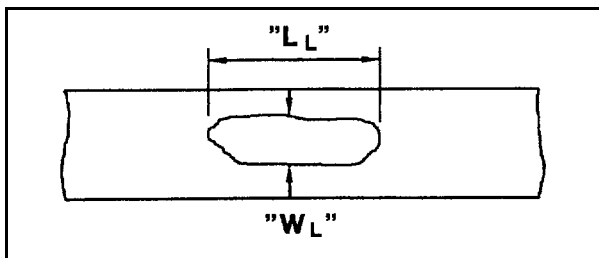
$$\text{End Loss} = L_2 = (L \times W) - (L_R \times W)$$

Center loss is defined as any loss of thermoplastic that extends entirely across the marking between its two ends. The loss is determined as the length of loss along the centerline multiplied by the nominal width of the marking.



$$\text{Center Loss} = L_3 = (L_L \times W)$$

Interior loss is the loss of thermoplastic contained entirely within the edges of the marking. The area of loss is calculated as the length of loss in the longitudinal direction multiplied by the width measured in the transverse direction.



$$\text{Interior Loss} = L_4 = L_L \times W_L$$

Total Percentage Retained Calculation:

$$\text{Total Loss} = L_1 + L_2 + L_3 + L_4$$

$$\% \text{ Retained} = \frac{\text{Nominal Area} - \text{Total Loss}}{\text{Nominal Area}} \times 100$$

INSTALLATION, MAINTENANCE, AND REMOVAL

Thermoplastic is regarded as the most durable delineation technique. Evidence also suggests that this durability is traded at the expense of ease of handling. Thermoplastic probably requires more care for

installation, maintenance, and removal than any other material. The most important concerns for proper handling of this material are discussed below.

Installation

Thermoplastic installation is a delicate process. The high temperatures involved and the material's extreme heat sensitivity require that a high quality control level in a thermoplastic marking operation. The following discussions provide guidance on the most critical aspects of thermoplastic application.

Primer-Sealers

The type and condition of the pavement during application on AC pavements is important for a good bond. Experience shows that adhesion on AC pavements is improved over PCC. The bituminous surface probably softens from the heat of application, and the thermoplastic then fuses more completely with the road. Good adhesion may require cleaning and/or application of a primer-sealer to the surface before marking.

If the type of pavement and the recommendation of the supplier warrant, a primer-sealer should be used. The New York State Department of Transportation (NYSDOT), with a number of other agencies, reported no difference in performance with or without primers when applied to AC pavements.⁽⁵⁵⁾ However, most material suppliers recommend the use of a primer-sealer on PCC and old bituminous pavements.

After tests of hot-extruded thermoplastic installations, the NYSDOT specified the use of epoxy primer on PCC. The large, automated, hot-spray equipment used in California is equipped to lay a two-component epoxy directly ahead of the spray thermoplastic.⁽⁵⁸⁾ The most commonly used primer in recent years is an epoxy resin.

Synthetic rubber-based primers have not proven as effective.

Careful application of rapid-drying epoxy primer coatings is necessary for good bonding. For example, evidence suggests that the thermoplastic materials should be applied when the primer is still tacky.⁽⁵⁹⁾ Failures have been reported when the primer was too dry or wet. One specification requires that the spray-applied primer remain tacky for at least 10 minutes at 73 degrees Fahrenheit (23 degrees Celsius).⁽⁵⁷⁾ One form of epoxy (with linseed oil) requires 24 hours of curing time.

There is also little agreement on whether thermoplastic should be applied over paint. There is evidence to suggest that a better bond is achieved on bare pavement. The highway agencies that maintain their own equipment and use their own forces for application appear to have developed unique methods. In some instances, neither PCC nor AC surfaces are pretreated, despite the supplier's recommendations. Yet some highway agencies will confidently estimate an 8- to 10-year service life based on past experience.

There appears to be no agreement on whether priming or cleaning of the pavement is the better method of pretreatment. There is also little agreement on the optimum application rate of primer. It depends on age, porosity, and texture of the pavement, as well as on the active solid contents of the epoxy solution used. Wet film thickness of primers ranges from 2 to 5 mil (0.3 to 0.13 millimeter) and is normally based on the manufacturer's recommendation. One study recommends 2 mil (.05 millimeter) as adequate.⁽⁵⁸⁾

Storage and Field-Handling of Materials

Hot-applied thermoplastic materials are available in block or granular form. They are packaged in cardboard containers or heavy-duty bags weighing 20 to 50 pounds

(9 to 23 kilograms). The containers should be stacked flat and stored on pallets in a dry place. Water or dampness will not harm the materials but may weaken or otherwise damage the cardboard containers.

Dirt, residue from the cardboard, or the polyethylene liner will contaminate the material. Take care to protect the material so that these pollutants are not accidentally loaded into the melting kettle.

The daily supply of cartons or bags to be carried on the truck bed should be covered. If the cardboard containers do get wet, all paper and other residue should be removed and the material allowed to dry before use.

Before loading, the bulk material should be broken up with a hammer while still in the carton. The carton should then be opened, placed over the kettle, and tilted to empty the material into the melting pot.

Sometimes thermoplastic will be supplied in containers that are made of thermoplastic material compatible with the marking material. In this case, the whole container is simply loaded into the melting kettle, and there are no problems with liners or other related contaminants. However, the outsides of the containers should be checked for dirt and other contaminants.

Application Methods

Formulations differ for application by extrusion or hot spray. They also differ for use in hot or cold climates. Often, an alkyd-based (synthetic resin) material is used in northern areas, applied by extrusion. A hydrocarbon-based (organic compound) material is used for spray application in more temperate climates. Suppliers will make a compound according to a highway agency's specifications, though they may recommend minor variations.

The various categories of thermoplastic installations require different application

techniques. In selecting the most appropriate thermoplastic materials, consider the physical requirements for each application to achieve a proper bond, as well as the equipment and staffing requirements.

The type of installation (transverse or longitudinal markings), type of facility (urban or rural), type of pavement, magnitude of the installation, and other project characteristics will influence the method of application. For example, a small intersection project to install crosswalks or stop bars will differ from a major improvement project in which delineation markings are a line item in the construction contract.

Extrusion

Extrusion application of thermoplastic had been the method of choice for several years, until the advent of hot-spray application. Hot-extruded thermoplastic marking operations take place at about 3 miles per hour (5 kilometers per hour), and are ready for traffic 2 to 10 minutes after application. Typical application thickness is 125 mil (3.2 millimeters).

In small-scale stripers, extrusion is typically accomplished with an extrusion die, or shoe. Material is heated in a jacketed kettle. The machine then passes a predetermined amount of material from the kettle into the die. The die contains a gate that is sized so that a certain thickness of material is deposited on the pavement. Then the process repeats itself. In this way, the temperature of the remaining material is kept constant, without having to incorporate the extrusion die into the heating mechanisms. This process is called *gravity extrusion*.

Ribbon extrusion, more common on large-scale stripers, uses a pressurized gun to lay the material. Ribbon extrusion is capable of producing the same sharp, crisp edges as those marked by using gravity extrusion.

Spray

The development of the hot-spray application technique for thermoplastic is considered by many to represent a significant breakthrough in delineation technology.⁽⁵⁷⁾ The spray process differs in that the hot thermoplastic is combined with pressurized air. The combination forces the material onto the pavement. Typical applications from large-scale stripers can take place at 9 to 12 miles per hour (15 to 19 kilometers per hour), and are ready for traffic in less than one minute. Spray applications are typically thinner than hot-extruded applications, usually between 60 and 90 mil (1.5 to 2.3 millimeters) thickness.

Major advantages with hot-sprayed thermoplastic include the ability to apply thinner coatings, better bond with the pavement, and better distribution and retention of glass beads. Also, the difficulties of maintaining a high temperature in the material during extrusion is largely eliminated by the spray process. Moreover, the hot-sprayed material hardens quickly upon application, lessening the sensitivity to pavement temperature.

Application Equipment

Molten thermoplastic can be extruded or sprayed onto the pavement by means of a manually operated device for small runs (figure 32), or by large automated stripers for major construction projects (figure 33). Typically, 2,000 pounds (908 kilograms) of thermoplastic materials supplied in granular or block form will yield approximately 6,600 feet (2 kilometers) of 4-inch (10-centimeter) marking with a 90-mil (2.3-millimeter) thickness.

The small-scale, manual striper usually has a melting pot that holds a manual mixing paddle to keep the thermoplastic from segregating or scorching. There is also a spigot and die, and a bead hopper and dispenser. In one design, the striper is

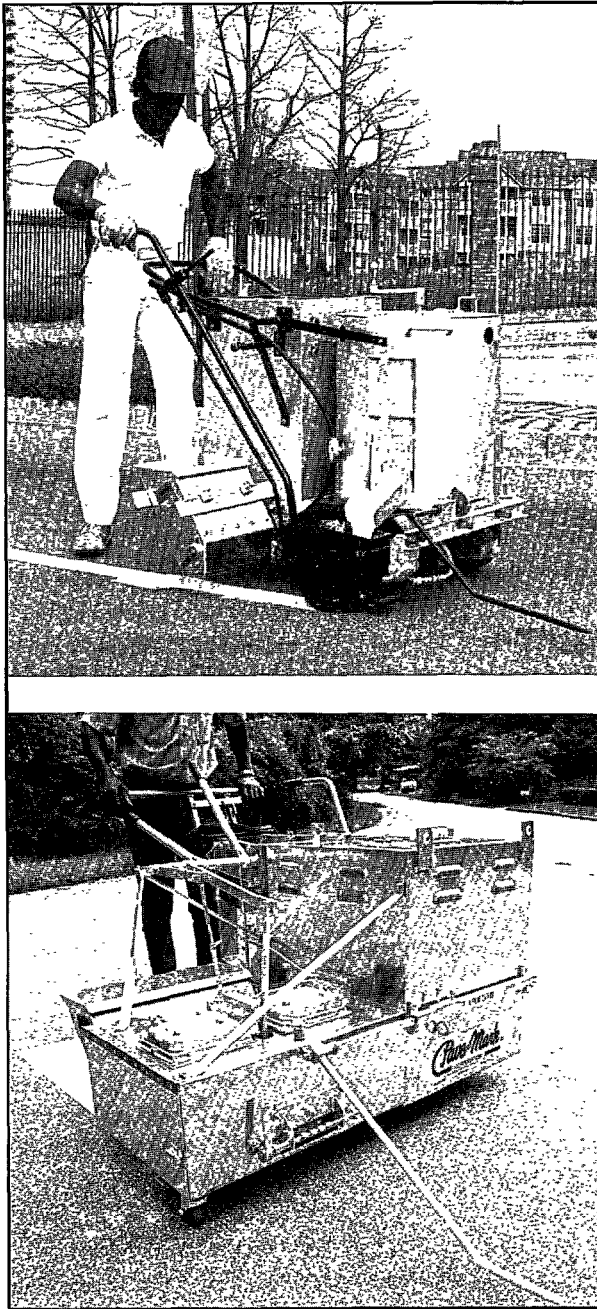


Figure 32. Small thermoplastic application equipment

equipped with a propane tank to fuel the burner under the melting pot. Another striper has an auxiliary unit for heating the materials after which they are transferred to the dispensing unit (figure 34). An infrared burner over the extrusion die can be used to maintain the temperature during

application. For manual, hot-spray application, the striper draws its compressed air supply through a long hose from a small truck-mounted machine. Small-scale stripers have an average capacity of about 12 gallons (45.4 liters) or about 100 pounds (45 kilograms) of molten thermoplastic.

Truck- or skid-mounted thermoplastic stripers are self-contained units with large melters, automatic agitators, heaters, electronic controls, intermittent timers that control the flow of spray to form solid or broken markings, material dispensers (extrusion die or spray nozzle), bead hoppers, and bead dispensers. Large-scale stripers range in size from a 1,000-pound (454-kilogram) to a 3,000-pound (1,360-kilogram) capacity melting pot (figure 35). Applications using these stripers are often contracted. The equipment costs can exceed \$150,000 and local staffs are seldom experienced in operating such complex machinery.

Some highway agencies maintain a small-scale striper for maintenance jobs or small installations, such as new crosswalks or stop bars. Large installations are either bid separately (for existing pavements) or are included as part of a new construction or resurfacing contract. There are, however, a number of highway agencies that prefer to purchase medium-sized stripers and conduct their own marking activities, with assistance from the material's supplier, if needed. Crew sizes range from two workers for manual application to as many as five workers for the largest operations. This does not include following vehicles or other protection and traffic control personnel.

Thickness of Applied Material

Correct application thickness is the subject of some debate. If durability is a function of thickness, thicker markings will last longer but require more material, thus more cost. It can be argued that this extended service life may outlast the

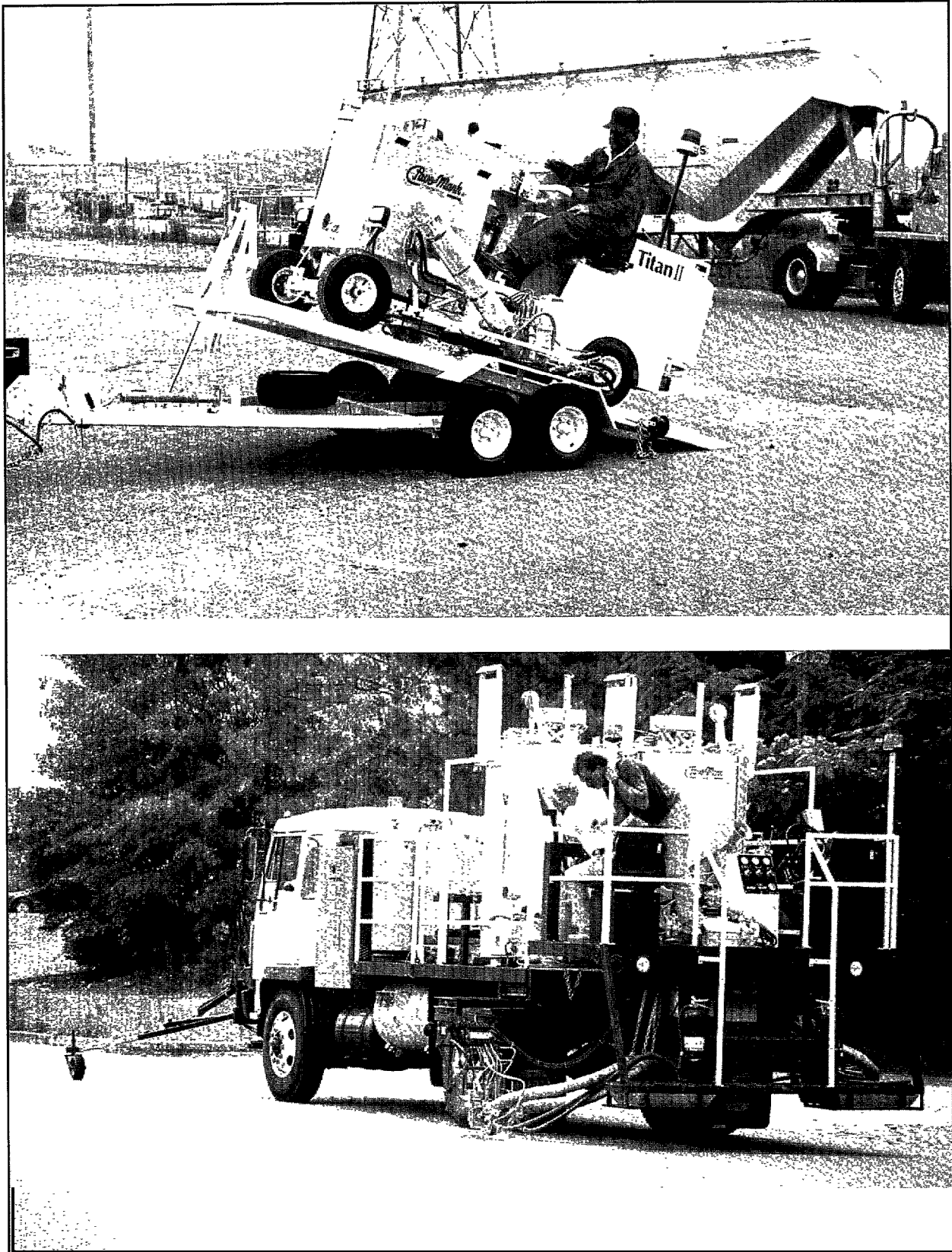


Figure 33. Large-scale thermoplastic application equipment

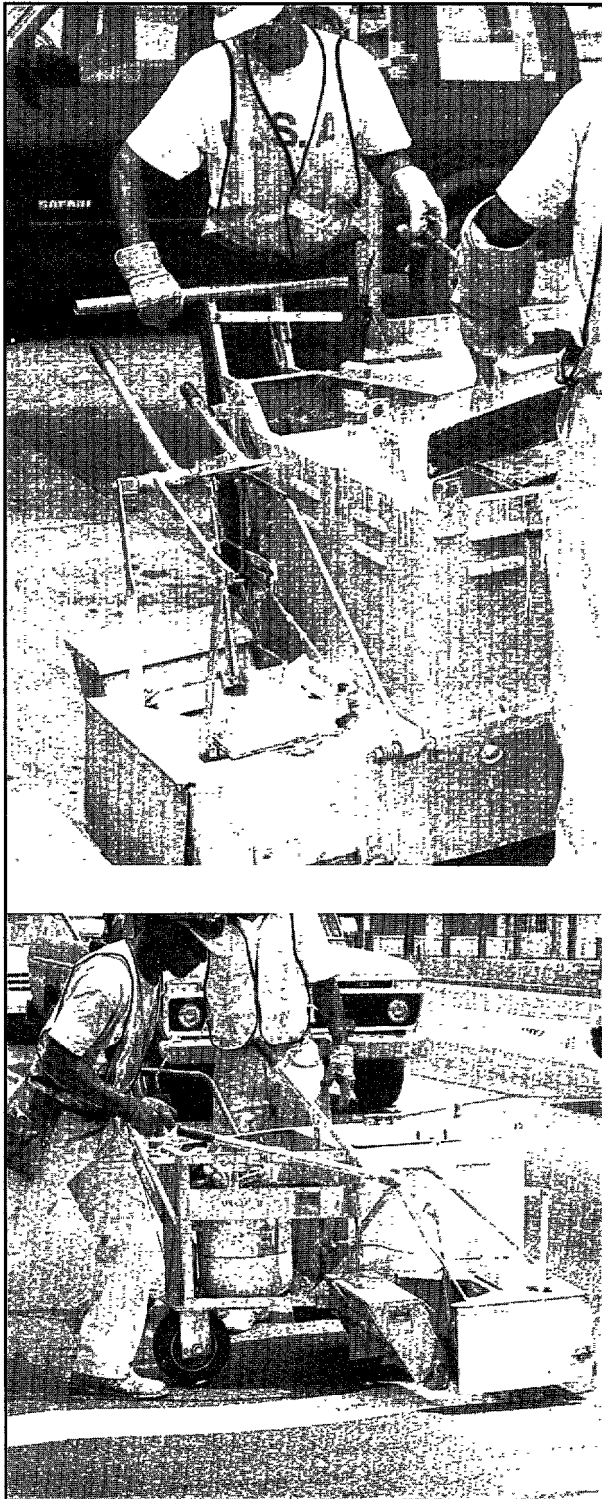


Figure 34. Loading and extruding thermoplastic

retroreflective properties, and, in some cases, the pavement itself. The value of a

6- to 10-year service life is minimal if the pavement is subject to resurfacing during this time. Similarly, bead loss may render the marking ineffective at night before this time elapses.

Thicker markings (90 to 125 mil/2.3 to 3.2 millimeters) provide better wet night visibility when the beads are still in place, but are more vulnerable to snowplow activity. In practice, the thicker applications continue to be used more than thinner markings. This approach is more flexible in that the markings can then be either extruded or sprayed.

However, the extrusion process is more compatible with thick applications, especially if 125 mil (3.2 millimeters) is desired. The spray process is best suited to applications of 90 mil (2.3 millimeters) or less. The thinner coatings have generally performed well and are usually more cost-effective.

Proponents of thinner applications (40 to 60 mil/1.0 to 1.5 millimeters) report acceptable retroreflectivity and durability over service lives of 3 to 4 years. Material costs are lower, application is faster, and damage from snowplow activity is less. Wear of thermoplastic material has been estimated at an average of 10 mil (0.25 millimeter) loss per year. Normal wear includes studded tire damage, traffic abrasion, and losses to snowplow activity. Thus, a marking of 40 mil (1 millimeter) could be expected to survive three to four years.⁽⁵⁷⁾

However, the thicker applications have a higher profile, and may therefore provide better wet night visibility. The thinner applications do not extend as far above the pavement and are more easily covered by surface water film. However, new advances in binder technologies have made use of a much larger sieve size of glass beads to be used with good durability. Large glass beads enhancement of wet night visibility is discussed in chapter 2. With these

advances, the most cost-effective technique is probably a spray process with a combination of intermix beads and large drop-on glass beads.

When selecting a thickness for a thermoplastic marking, there are a myriad of variables to be considered. A thickness must be selected that will enable the marking to perform especially well in the environment for which it is intended. It should be noted that this process must not be performed independent of the other variables. All aspects of application (material used, application method, type of pavement, and so on) must be considered interactively in order to achieve cost-effectiveness.

Maintenance

One of the advantages of thermoplastic is its durability. Depending on the material used and the roadway characteristics, thermoplastic can provide virtually maintenance-free delineation for years. Some of the maintenance concerns related to thermoplastic are discussed below.

Staining

In hot climates, thermoplastic markings can become discolored or badly stained by tire tracks, particularly on bituminous pavements. This degrades the daytime contrast and visibility. Thermoplastic materials are, however, somewhat self-cleaning during rainy weather. That is, the tire action on wet markings will remove most of the stains. In hot, dry areas, it may be desirable to consider cleaning the markings by washing with a mild detergent.

Patching

Thick, extruded thermoplastic installations are especially vulnerable to chipping if the pavement bond is weak, the pavement bond is faulty, or the internal cohesion of the pavement itself is unstable. Almost all thermoplastic materials, hot- and cold-applied, can be patched by placing a thin overlay of compatible material onto the missing portion of the old marking. This is usually accomplished with a manual applicator.

Replacement

When thermoplastic markings are no longer effective and must be replaced, it is

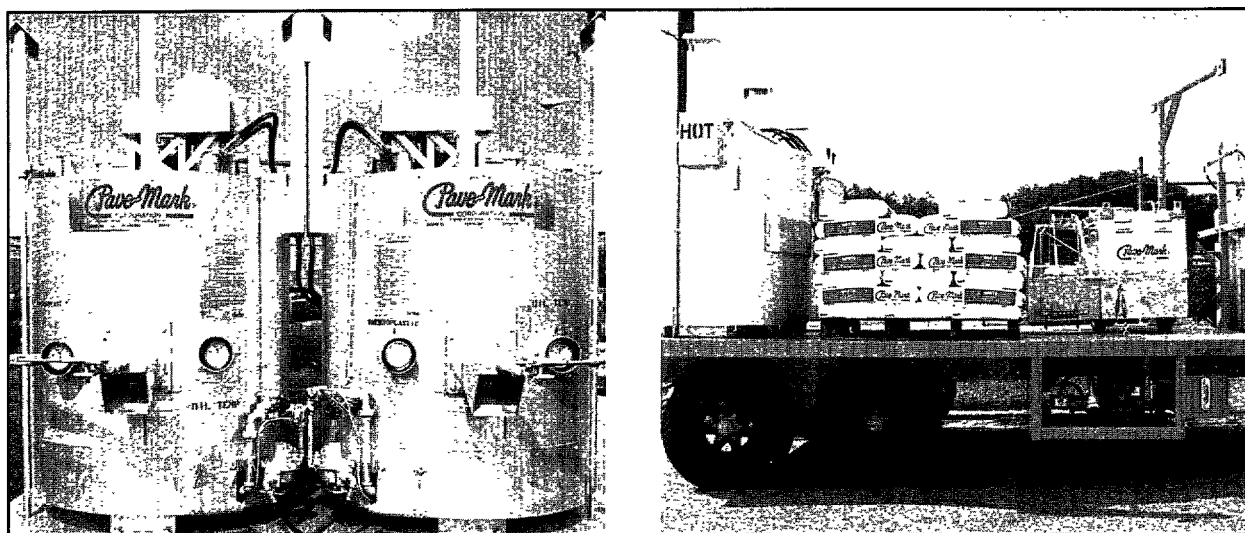


Figure 35. Typical melting kettles used in thermoplastic application

common practice to renew the markings with an overlay of compatible material. This can be treated as a scheduled maintenance activity, as a separate project, or as part of a larger improvement program. Depending on the size of the installation and agency policy, the work may be performed by a highway agency's forces or a contractor can be hired.

In some cases, thermoplastic markings outlive their retroreflective properties. One highway agency experimented with using paint and glass beads overlaying the old thermoplastic to obtain night visibility. The paint was used as a binder to retain the beads since much of the thermoplastic marking was still in place. If the paint adheres to the thermoplastic and if the thermoplastic base is securely bonded to the pavement, this could be an inexpensive method of upgrading markings with inadequate retroreflectivity. However, there is no available information on the performance of this combination.

Removal

Thermoplastic markings can be difficult to remove. The properties that enhance durability, such as thickness and integral bond with the pavement, deter easy removal.

On both PCC and AC, removal of thermoplastic markings scars the pavement. The extent of the scar will depend on the method of removal employed.

Markings in place will be completely covered during any type of roadway resurfacing or rehabilitation project.

Sandblasting

Sandblasting is used frequently for large-scale removal jobs. The physical characteristics of this method were discussed in chapter 4. One operation features a high-pressure water jet used in conjunction with sandblasting. This

minimizes the residual sand on the pavement and enhances the effects of the sandblasting.

Excess Oxygen

The excess oxygen paint removal equipment described in chapter 4 has also been used to remove hot-sprayed thermoplastic. In this case, the hot flame melts the thermoplastic, and the molten thermoplastic is removed with a straight hoe. Subsequently, the residual marking is reburned and the burned residue is brushed away leaving only a slight indication of where the marking had been. This will disappear with traffic wear.

Grinding or Chipping

For smaller jobs, an air hammer and chipping blade can be used. Take care on asphalt surfaces to prevent excessive damage to the pavement. To remove an occasional arrow or legend, manual removal using a hammer and chisel can do a satisfactory job.

In recent years, improvements in cutter wheels and other technologies have made large-scale grinders feasible. These are marketed by a variety of vendors, several of which also sell products for pavement marking. Highway agencies' experience with these large-scale grinders has been mixed for different products, and little formal research has been made available for evaluating different models of grinders.

INSPECTION

The operational procedures for the application of hot-applied thermoplastic markings are quite similar to those for application of paint. Where no previous markings exist, the roadway must be premarked with guidelines using the same methods described for paint application (see chapter 4). Although highway agencies' specifications differ, most call for application on dry and clean pavement. Pavements

should be tested for dryness, using the litmus or other tests. More often, a subjective judgment is made by the engineer in charge. Morning dampness can cause early failure of the markings.

The techniques for removing loose dirt, old paint, oils, and other contaminants include sandblasting, airblasting, hydroblasting, brooming, acid etching and grinding. Some agencies report no precleaning requirement for bituminous pavements. The most appropriate technique depends on the condition of the surface and whether any residual paint must be removed. Sandblasting and acid etching are usually restricted to concrete pavements. Better adhesion is reported for installations in which the concrete was subjected to light grinding before application.

Clean and Dry Pavement

The pavement should be dry with no surface dampness, dew, or subsurface wetness. As mentioned in chapter 4, marking is too often begun before the pavement is sufficiently dry for application.

Thermoplastic should not be applied over old preformed tape markings. If thermoplastic materials are being applied on top of old thermoplastic markings, the base layer must be in stable condition and the old material should still have an adequate bond with the pavement. Thermoplastic applied on top of markings that failed from inadequate bond strength will simply peel off the pavement with the old markings.

If the old layer of markings still has an appreciable quantity of surface beads, it should be roughened by brooming or light grinding. The same applies to premarkings that were applied with a top dressing of glass beads.

Air Temperature

Ambient air temperature should be at least 55 degrees Fahrenheit (13 degrees

Celsius) for application of the majority of thermoplastic materials. If the manufacturer specifies some other temperature, that value should be used. The wind chill factor should be considered when determining whether it is warm enough to begin marking operations. The wind chill factor will help determine how quickly the material on the pavement will cool. If the wind chill is too low, the material will cool before it has had an opportunity to bond with the pavement. If the wind chill factor is below 45 degrees Fahrenheit (7 degrees Celsius), thermoplastic materials should not be applied.

Pavement Temperature

The pavement temperature is probably the single most important factor in applying thermoplastic materials. The pavement temperature will govern the rate of cooling of the material, even more than the air temperature. This is because the rate of heat transfer to the pavement from the material is by conduction and transfer to the air is by convection. Under any normal conditions, heat transfer by conduction is much quicker than by convection.

The pavement should be at a temperature of at least 55 degrees Fahrenheit (13 degrees Celsius). This may be measured with a standard surface temperature thermometer.

Material Temperature

Material temperature required will vary more than any other parameter. The optimum value may vary for different materials, and the laws of heat transfer dictate that maintaining close tolerances at the high temperatures required for thermoplastic application is difficult. These are often hundreds of degrees higher than temperatures for paint application. Normal operating temperatures are in the range of 400 to 450 degrees Fahrenheit (204 to 232 degrees Celsius), with the optimal value

between 425 and 435 degrees Fahrenheit (218 and 224 degrees Celsius).

Other Tests

Other than pavement pretreatment and temperature concerns, inspection of thermoplastic markings is essentially the same as for paint. Markings should first be visually inspected for crisp edges and minimal deviation or overspray. The same tests as for paint may then be performed. These include material thickness, pocket microscope inspection for bead quantity and distribution, and the sun-shadow retroreflection test.

Thermoplastic materials are very sensitive to the variables governing application. Table 6 has been included to help diagnose problems that may exist in the application process. It also presents some possible solutions to these problems. This table is taken directly from manufacturers' literature for correcting problems that occur with their materials.

Table 6. Common problems with thermoplastic

If Line Appears:	Problem Is:	To Correct:
Smooth, shiny, glossy	No beads in marking, resulting in no retroreflectivity, caused by bead gun malfunction	<ul style="list-style-type: none"> • Repair bead applicator • Increase bead application rate • Move point of bead application
Smooth, with slight dimples	Drop-on beads sunk too low, resulting in lower retroreflectivity, caused by material being too hot	<ul style="list-style-type: none"> • Increase bead application rate • Cool material, staying above 425 degrees Fahrenheit
Glazed or "icy"	Beads too high, not adhered well, will wear off quickly, caused by material being too cold or bead gun too far from application point	<ul style="list-style-type: none"> • Ensure thermoplastic temperature is 425-435 degrees Fahrenheit • Move point of bead application
Cratered	Beads popped out, resulting in lower retroreflectivity, caused by material being too cold and/or poor bead adhesion	<ul style="list-style-type: none"> • Ensure thermoplastic temperature is 425-435 Fahrenheit
Rough around edges	Inconsistent bond, resulting in less durability, caused by material being applied too cold/and too thin	<ul style="list-style-type: none"> • Ensure marking is proper thickness • Ensure thermoplastic temperature is 425-435 degrees Fahrenheit
Wavy, with irregular edges	Flow-out of material edge is not well-defined, caused by material being too hot or too liquid, application pressure being too high, extrusion gate open too wide, and/or road surface being too uneven	<ul style="list-style-type: none"> • Ensure thermoplastic temperature is 425-435 degrees Fahrenheit • Adjust application equipment • Slow application rate on rough surface
Greenish yellow	Scorching resulting in thermoplastic becoming brittle and less durable, caused by overheating or too many reheats	<ul style="list-style-type: none"> • Discard material
Dingy, dull yellow	Scorching resulting in thermoplastic becoming brittle and less durable, caused by overheating or too many reheats	<ul style="list-style-type: none"> • Discard material
Pitted	Trapped moisture, trapped primer or trapped air, all of which weaken bonding	<ul style="list-style-type: none"> • Perform moisture test • If moisture is present, STOP OPERATION • If moisture test is negative, determine if surface is open-graded. To avoid air entrapment on open-graded surfaces, slow application rate and ensure thermoplastic temperature is 425-435 degrees Fahrenheit.

If Line Appears:	Problem Is:	To Correct:
Lumpy	Charred material or unblended pigments and filler resulting in lower durability	<ul style="list-style-type: none"> • Determine problem by removing a lump from the melter and cutting it open • If the lump appears burnt or dark in color, material is charring inside heating system. Remove all visible lumps from melter and screen material before applying • If the lump appears grainy or unmixed, the resin and/or pigments are unmelted. Hold the thermoplastic in the melter at 425-435 degrees Fahrenheit until the lumps dissolve
Stretched or pulled	Inconsistent bond and poor durability caused by material being applied too cold and too rapidly	<ul style="list-style-type: none"> • Ensure thermoplastic temperature is 425-435 degrees Fahrenheit • Adjust application speed
Scarred or gapped	Weakened bond caused by charred material or a rock drug through the marking	<ul style="list-style-type: none"> • Remove lump from melter and cut open to determine if the materials is charred. If so, remove all visible lumps and screen material before applying • Clean Surface
Uneven at beginning or end of marking	Poor appearance, cut-off not sharp because applicator is not adjusted correctly	<ul style="list-style-type: none"> • Adjust applicator • Ensure thermoplastic temperature is 425-435 degrees Fahrenheit
Too much dribbling between skips	Poor appearance caused by poorly adjusted applicator	<ul style="list-style-type: none"> • Adjust applicator • Ensure thermoplastic temperature is 425-435 degrees Fahrenheit
Marked by tire tracks	Road opened to traffic before thermoplastic has cured or an insufficient amount of beads has been used	<ul style="list-style-type: none"> • Keep traffic off of marking for longer period of time • Increase bead application rate